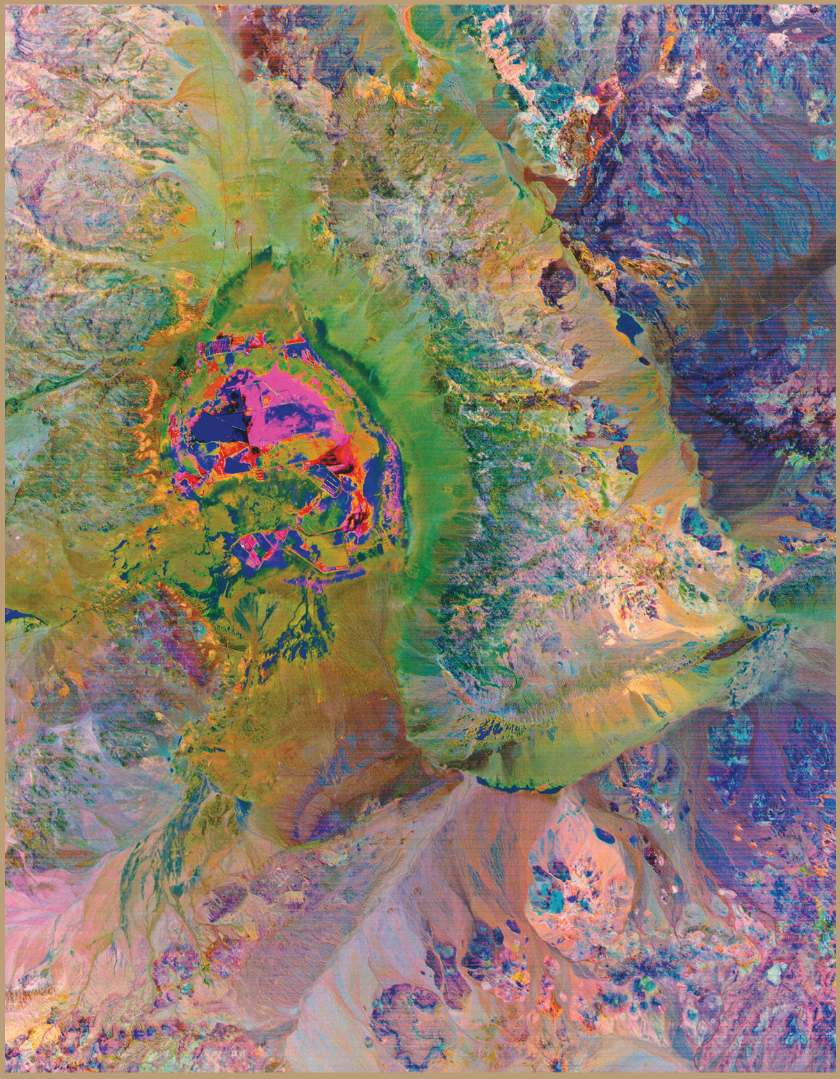
USGS
science for a changing world

Late Cenozoic Geology and Lacustrine History of Searles Valley, Inyo and San Bernardino Counties, California



Professional Paper 1727

U.S. Department of the Interior
U.S. Geological Survey

This page left blank intentionally.

Late Cenozoic Geology and Lacustrine History of Searles Valley, Inyo and San Bernardino Counties, California

By George I. Smith

Detailed geologic maps of Searles Valley document a late Cenozoic, primarily Quaternary, sedimentation history. The Quaternary sediments prominently include the 150-2 ka Searles Lake Formation, described and named herein. The Searles Lake Formation is divided into seven, dominantly lacustrine units, which can be correlated with subsurface units known from drill cores in now-dry Searles Lake, in the center of the valley. Together, these surface and subsurface sediments help chart the region's complex recent climatic history.

Professional Paper 1727

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

This report and any updates to it are available online at:
http://pubs.usgs.gov/pp/1727/

For product and ordering information:
World Wide Web: http//www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS (1-888-275-8747)

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov/
Telephone: 1-888-ASK-USGS (1-888-275-8747)

Suggested citation:
Smith, G.I., 2009, Late Cenozoic geology and lacustrine history of Searles Valley, Inyo and San Bernardino Counties, California: U.S. Geological Survey Professional Paper 1727, 115 p., 4 plates.

Cataloging-in-publication data are on file with the Library of Congress (URL http://www.loc.gov/).

FRONT COVER
False-color satellite image (Landsat Thematic Mapper) of Searles Valley, California. North is at the top. The valley is flanked by the Slate Range on the east and the Argus Range and Spangler Hills on the west. The linear feature trending east-northeast from southwest corner of image is the Garlock Fault. Scale: widest part of valley near middle of Searles Lake is 15 km; vertical dark line north of lake is 1,800-m-long airport runway. Image is a band-ratio composite, in which blue indicates Fe^{3+} in the reflecting material, green indicates Fe^{2+}, and red reflects clay, CO_3, and vegetation. Yellow is produced by mixtures of red and green. Searles Lake (left center) is largely magenta and dark blue, colors caused by differing mixtures of Fe^{3+}-bearing clays and CO_3 (straight lines on the lake surface are roads and evaporating-pond dikes). Alluvial fan surfaces east and north of the lake are mostly green because of the abundance of Fe^{2+} in detritus from metamorphic rocks from the Slate Range (note erosional shorelines northeast of lake and curved offshore bars north of lake); fans west and south are also green but have areas of blue (more Fe^{3+}-bearing volcanic rocks and desert varnish) and red (CO_3- and clay-rich lacustrine sediments). Orange bands on the flanks of the Argus Range and Spangler Hills are caused by the impure CO_3 in massive tufa deposits near the highest lake shoreline (carbonate bedrock in mountain areas in northeast part of image also shows orange hues). Photograph courtesy of Ronald Blom, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. For geographic reference, see figure 1; for geology, see plates.

Foreword

George I. Smith received a Bachelor of Science Degree in chemistry from Colby College, Maine, in 1949 and a Ph.D. in geology from the California Institute of Technology in 1956. He joined the U.S. Geological Survey (USGS) full time in 1952, and after a short period of geologic mapping and drilling for saline minerals in the northern Mojave Desert and Death Valley, he began a career-long interest in the sediments, saline mineral assemblages, and paleoclimatic significance of Searles (dry) Lake, California. After 1960, he was the USGS commodity specialist for several commercially produced saline minerals.

After recognizing the role that past climate change played in the accumulation of sediments and saline minerals, Smith broadened his investigations to determine the magnitudes, timing, and meteorological causes of past climate and consequent hydrologic changes evidenced in many of the continental saline deposits of the southwestern United States. Much of the understanding of the climate record in Searles Valley has been based on studies of a 930-m drill core through the sediments beneath the dry lake, which provided a 3.2-million-year climate history to compare to the deep-sea record. The present study integrates that subsurface work with the deposits that crop out on the surface of the valley, from which Smith defines the Searles Lake Formation to include those deposits of the past 150,000 years. During his many years of studying the outcrops in Searles Valley and adjacent areas, Smith frequently complemented traditional fieldwork with aerial reconnaissance from a small plane he piloted himself. He also provided the leadership for drilling and studying a 323-m core hole in Owens Lake that provided an 800,000-year climate record. During pluvial (wet) periods in the Pleistocene, Owens Lake was the first lake in a chain that included Searles Lake and ultimately emptied into Death Valley.

George Smith served as Chief of the Light Metals and Industrial Minerals Branch of the USGS between 1966 and 1969. In 1978, he organized the USGS Climate Change Program, and he then served as its coordinator for its first 3 years and as the Department of the Interior representative to the Climate Research Board of the National Research Council. He patiently explained the importance of geologic studies of past climates as an aid to understanding climate change and for the modeling of future climate. Smith received the Meritorious Service Award of the Department of the Interior in 1983. He is an elected fellow of the Geological Society of America and of the Mineralogical Society of America. After retiring from the USGS in 1995, Smith received a Pecora Fellowship for 1995 and continued working as an Emeritus USGS scientist until 2005.

The original manuscript and geologic maps for this work received colleague review in 1992 and 1993 and approval from the USGS Volcano Hazards Team in 1996. They were edited by the then Western Publications Group in 1999 and 2000 and returned to the author. Various revisions were made to the edited manuscript over the next several years. In 2004, George Smith had a stroke and further work on the manuscript was undertaken with the assistance of his stepdaughter Michelle Ono. In 2005, the manuscript was returned to the Volcano Hazards Team for publication. Careful review of the 2000 and 2005 versions by USGS editor Peter Stauffer indicated that the earlier version was more internally consistent, and consequently this published version is largely based on the 2000 version, with some updates and additions from the 2005 version.

The final editing of the manuscript was done by Peter Stauffer, and final editing of the geologic map plates was done by Jan Zigler. Joel Robinson took the commercially scanned digital versions of Smith's original hand-drafted geologic maps and processed them to finalized versions for production. Throughout these final stages, Manuel Nathenson of the Volcano Hazards Team served as author's representative. Some degree of judgment was required in the process of transforming the supplied materials to the final version presented here, and those involved in it have made every effort to be faithful to the author's original work.

Suzette M. Kimball
Acting Director

Contents

Plates

[In pocket]

Figures

Tables

Late Cenozoic Geology and Lacustrine History of Searles Valley, Inyo and San Bernardino Counties, California

By George I. Smith

Abstract

Searles Valley is an arid, closed basin lying 70 km east of the south end of the Sierra Nevada, California. It is bounded on the east and northeast by the Slate Range, on the west by the Argus Range and Spangler Hills, and on the south by the Lava Mountains; Searles (dry) Lake occupies the north-central part of the valley. During those parts of late Pliocene and Pleistocene time when precipitation and runoff from the east side of the Sierra Nevada into the Owens River were much greater than at present, a chain of as many as five large lakes was created, of which Searles Lake was third. The stratigraphic record left in Searles Valley when that lake expanded, contracted, or desiccated, is fully revealed by cores from beneath the surface of Searles (dry) Lake and partly recorded by sediments cropping out around the edge of the valley. The subsurface record is described elsewhere. This volume includes six geologic maps (scales: 1:50,000 and 1:10,000) and a text that describes the outcrop record, most of which represents sedimentation since 150 ka. Although this outcrop record is discontinuous, it provides evidence indicating the lake's water depths during each expansion, which the subsurface record does not. Maximum-depth lakes rose to the 2,280-ft (695 m) contour, the level of the spillway that led overflowing waters to Panamint Valley; that spillway is about 660 ft (200 m) above the present dry-lake surface.

Several rock units of Tertiary and early Quaternary ages crop out in Searles Valley. Siltstone and sandstone of Tertiary age, mostly lacustrine in nature and locally deformed to near-vertical dips, are exposed in the southern part of the valley, as is the younger(?) upper Miocene Bedrock Spring Formation. Unnamed, mostly mafic volcanic rocks of probable Miocene or Pliocene age are exposed along the north and south edges of the basin. Slightly deformed lacustrine sandstones are mapped in the central-southwestern and southern parts of the study area.

The Christmas Canyon Formation and deposits mapped as older gravel and older tufa are extensively exposed over much of the basin floor. The older gravel unit and the gravel facies of the Christmas Canyon Formation are boulder alluvial gravels; parts of these units are probably correlative. The lacustrine facies of the Christmas Canyon Formation includes the Lava Creek ash, which is dated at 0.64 Ma; the older tufa deposits may be equivalent in age to those sediments.

Most of this study concerns sediments of the newly described Searles Lake Formation, whose deposition spanned the period between about 150 ka and 2 ka. Most of this formation is lacustrine in origin, but it includes interbedded alluvium. To extract as much geologic detail as possible, criteria were developed that permitted (1) intrabasin correlation of some thin outcrop units representative of only a few thousand years (or less), (2) identification of unconformities produced by subaerial erosion, (3) identification of unconformities produced by sublacustrine erosion, and (4) correlation of outcrop units with subsurface units.

The Searles Lake Formation is divided into seven main units, many of which are subdivided on the five larger scale geologic maps. Units A (oldest), B, C, and D are dominantly lacustrine in origin. The Pleistocene-Holocene boundary is placed at the top of unit C. In areas that were a kilometer or more from shore at the time of deposition, deposits of units A,B, and C consist of fine, highly calcareous sand, silt, or clay; nearer to shore they consist of well-sorted coarse sand and gravel. Unit A has been locally subdivided into as many as four subunits, unit B into six subunits, and unit C into six subunits. The finer facies of units A, B, and C contain such high percentages of $CaCO_3$ that they are best described as marl. Sediments of unit C, and to a lesser extent those of unit B, are laminated with light- to white-colored layers of aragonite, calcite, or dolomite(?) that may represent seasonal deposits. Unit D, which is divided into two facies, is a pinkish silt with halite efflorescences that is locally overlain by a thin lacustrine gravel.

Units AB, BC, and CD, which are interbedded between the two single-letter units that make up their names, include both alluvial and lacustrine deposits. Unit AB is divided into as many as seven subunits, unit BC into two subunits, and unit CD is undivided. Where these units are alluvial, their lithologies range from pebble sand to boulder gravel that is poorly sorted and bedded. Soils developed on each unit are distinctive, and in most instances they serve as a basis for tentatively identifying each unit throughout the basin (as well as constraining the possible ages of overlying and underlying lacustrine sediments). Where these units are lacustrine, they are most commonly shallow water, well sorted sand.

The depositional intervals of the units that make up the Searles Lake Formation are estimated to be as follows (all estimated ages are in "uncorrected ^{14}C years"): unit A, 150 ka to

32 ka; unit AB, 32 ka to 24 ka; unit B, 24 ka to 15 ka; unit BC, 15 ka to 13.5 ka; unit C, 13.5 ka to 10.5 ka; unit CD, 10.5 ka to 6.0 ka; unit D, 6.0 ka to 2.0 ka. These ages are determined primarily by correlation with subsurface deposits that are dated by ^{14}C dates on organic carbon and U-series dates on salts.

Late Holocene deposits are mapped as (1) older alluvium, (2) playa silt, (3) windblown sand and colluvium, (4) windblown dune sand, and (5) active alluvium.

Tufa, deposited by a combination of organic and inorganic processes, is widespread. Major periods of growth of the relatively structureless “lithoid” variety of tufa occurred early during deposition of unit A, and deposition of the nodular, tubular, or lobate “nodose” variety of tufa occurred near the end of unit B time and the beginning of unit C time. Volumetrically, most of the tufa grew near the 1,800-ft (550 m) and just below the 2,280-ft (695 m) levels; the largest masses occur along the west side of the basin (see cover image) and in an area named The Pinnacles, where towers as high as 30 m are found.

Fossil snails, clams, and ostracods are found in many parts of the Searles Lake Formation, but they are especially abundant near the paleoinlet area. The snails and clams indicate fresh water conditions, which occurred most commonly in the inlet area. Ostracods tolerate a wider range of salinities and occur more widely. Vertebrate fossils were not found.

Shorelines, the most obvious geologic expressions of former lakes, are abundant around Searles Valley. Erosional shorelines have cut as much as 100 m into brecciated bedrock; depositional shorelines (beaches or tufa benches) are common, but their deposits tend to be thin. Gracefully curving offshore bars and spits, 2 to 10 m high, are prominent in the north and south ends of Searles Valley and near the middle of its west side. They were deposited subparallel to the shoreline, but their crests vary in elevation by as much as 10 m and it is clear that they were not deposited a uniform distance from shore. Most bars are asymmetrical, having slopes as steep as 25° on the uphill side but no more than 5° on the downhill side.

Several faults are mapped as having displacements of late Cenozoic age. The left-lateral Garlock Fault, 250 km long, bounds Searles Valley on the south and is the most geologically significant fault in the area. It displaces several of the mapped units of late Quaternary age but does not displace active or older alluvium deposits of late Holocene age. A prominent graben along the east side of the valley, and normal-fault extensions of it to the north and south, also represent Holocene displacements; alluvial deposits of the early Holocene unit CD are displaced, but late Holocene older alluvium deposits are not.

Certain paleolimnological aspects of the lakes that deposited the Searles Lake Formation can be reconstructed. Lake-water chemistry and pH are approximated from subsurface data on the mineralogies of salt layers, from outcrop data such as the mineralogy of salt efflorescences, and from the reconstructed salinities indicated by ostracod or mollusk suites. Laminated sediments are believed to indicate salinity stratification in the depositing lake; this requires the lower saline layer to be sufficiently dense to keep the stratification stable. Even when the lake was stratified, however, large amounts of $CaCO_3$ were deposited near the paleoinlet, where Ca-bearing inflow waters soon mixed with the high-pH, CO_3-rich lake waters, creating a “chemical delta.”

Nearshore high-energy environments of deposition in Searles Valley lakes produced beaches and bars composed of coarse sand and gravel. Many of these deposits are now well cemented by calcite. During deposition of the Searles Lake Formation, the deposits of unit A were composed of larger fragments than were the later deposits of unit B, which, in turn, were coarser than those of unit C, apparently indicating a long-term decrease in storm-wind intensities. Storm-current directions, reconstructed from the fragment composition of offshore bars, also indicate differences in storm-wind directions at different times and lake levels.

Combining the subsurface evidence of lake history with the evidence described herein allows the history of lake fluctuations to be reconstructed for the period between about 150 ka and the present. Between 150 ka and 140 ka, Searles Lake rose from a depth below the present dry-lake surface to its spillway level, now approximately at elevation 2,280 ft (695 m), 780 ft (235 m) above its floor at that time. From then until about 118 ka, it overflowed into Panamint Valley. Following this period of overflow, lake level lowered and fluctuated at intermediate levels until 35 ka. There was possibly a brief period of overflow at about 50 ka. These intermediate- to high-level stands were separated by brief lower level stands that are estimated to have occurred at periods centered at 107 ka, 79 ka, 69 ka, and 45 ka. Between about 35 ka and 23 ka, Searles Lake fluctuated every 1 to 2 thousand years between intermediate depths (when silt and clay were deposited) and shallow depths (when it deposited salts); it desiccated briefly at about 28 ka. This low- to intermediate-depth stage was followed by one of increased inflow, culminating in a period of overflow at about 16 ka. After falling to a low level between 15 ka and 13.5 ka, the lake again rose twice to overflow levels, then fell to desiccation levels at about 10.5 ka. Searles Lake has remained mostly dry since its desiccation at 10.5 ka, except for a period centered at about 3.5 ka when the lake surface rose to a level of about 1,800 ft (550 m).

Translating this record of lake fluctuations into paleohydrologic and paleoclimatic histories is complicated by uncertainties as to which of the several components of climate affected runoff volumes and lake-surface evaporation. A simplified model, however, suggests that the flow of the Owens River stayed between 2.5 and 4.5 times its present flow volume for most of the past 150 k.y. Its flow exceeded this range only about 14 percent of the time, and it fell below this range only 4 percent of the time—which includes the present. In fact, the past 10 k.y. is clearly the driest part of the past 150 k.y.

Over the full 3.2-m.y. period known from subsurface data, the climatic record is influenced by a geologic factor: the ever-increasing “rain shadow” produced by continuing uplift of the Sierra Nevada. Meteorological principles and subsurface evidence from Searles Valley and elsewhere support the existence of this climatic trend toward aridity, yet the longest sustained period of desiccation of Searles Lake was in the first third of that 3.2-m.y. period, as was the longest period of continuous perennial-lake deposition. This and many other lines of evidence show that the lake oscillations in Searles Valley have been products of climatic changes that exceed the impact of geologic and topographic changes. The durations of the most persistent and extreme climatic regimes in the Searles Valley area resemble phenomena found in the deep-sea record that have a 413-k.y. cycle length, which can be attributed to the Earth's orbital perturbations. During "intermediate" climatic regimes, however, the shorter duration, less extreme climatic changes in the Searles Lake record appear to reflect the orbital perturbations of shorter cycles that may have controlled the timing of high-latitude glacial events. It remains to be seen whether the glacial history of the east slope of the Sierra Nevada followed a timetable dictated by cooler temperatures related to high-latitude glaciation, or one that followed the 413-k.y. precipitation cycles recorded downstream by Searles Lake.

Introduction

Searles Valley is in southeastern California, about 200 km north-northeast of Los Angeles and 160 km east of Bakersfield. It lies near the southwest corner of the Basin and Range Province just north of the Mojave Desert and about halfway between the south ends of the Sierra Nevada and Death Valley (fig. 1*A*). The valley is crescent shaped and has an axial length of about 65 km and a maximum width of about 15 km. Searles Lake, a normally dry salt lake, occupies the widest part of the valley. The former towns of Pioneer Point, Trona, Argus, and Westend lie along its west edge (fig. 1*B*); in the early 1990s, the limits of Trona were expanded to include all four.

The climate in Searles Valley is arid. Annual temperatures during the period 1951 to 1980 averaged 19.0°C (66.2°F), but seasonal variation is great. Average temperature maxima and minima in July were 40.9°C and 22.4°C (105.6°F and 72.3°F); these extremes in January were 14.9°C and -0.2°C (58.9°F and 31.7°F). Mean annual precipitation was 100.3 mm (3.95 in), more than half of that amount falling in the first three months of the calendar year (National Oceanic and Atmospheric Administration, 1982). Interannual precipitation variability ranged from 43 mm (1.7 in) to 246 mm (9.7 in). Except during rain days, relative humidity varies diurnally from near 20 to 40 percent in early evening to 70 to 90 percent in early morning (G.F. Moulton, written commun., 1987).

Vegetation is sparse in Searles Valley; typical plants are those characterizing much of the Mojave Desert region, such as creosote bush (*Larrea tridenta*), hop sage (*Grayia spinosa*), desert holly (*Atriplex hymenelytra*), and burro bush (*Franseria dumosa*). In the adjoining mountain ranges, at elevations near or above 2,000 m (6,500 ft), Pinyon pine (*Pinus monophylla*) and joshua trees (*Yucca brevifolia*) grow locally.

The native fauna are numerous, but a brief list includes coyotes, rabbits, various rodents, tarantulas, quail, lizards, and snakes (rattlesnakes, gopher snakes, and other varieties). The wild burros that are commonly seen in these areas are not native but were introduced by early prospectors and travelers who brought them from the Middle East in the late 1700s and 1800s.

Mining of evaporite minerals from the deposits beneath the surface of dry Searles Lake has been an important part of the area's history. Since the late 1800s, individuals and small companies have owned or occupied land on the lake and produced selected industrial minerals. The first mineral having known value, borax ($Na_2B_4O_7$•10 H_20), was discovered in 1872 by the brothers John and Dennis Searles. They started production of borax from the west side of the lake in 1874 and prospered from it for 21 years, but in 1895 the operation was sold to the Pacific Coast Borax Company, who closed it. In 1908, soda ash (Na_2CO_3) production was attempted by the new California Trona Company, but it went into receivership the following year. Soon after, the company, revived under a new name (American Trona Company) built a small plant that was also designed to produce soda ash. First, however, they built a 35-mile-long railroad that connected the site of their future plant with the Southern Pacific Railroad at the southwestern tip of Searles Valley; the railroad was a success but the plant never produced any soda ash!

In 1913 the unowned parts of Searles Lake were withdrawn from prospecting and designated a potash reserve by the U.S. Government, which "discovered" potash (KCl) in Searles Lake brines, although its presence there had been known and discussed for several years (Gale, 1914, p. 309-312). As anticipated in the Government's action, after World War I started in 1914, the global price of potash increased tenfold (except in Germany, where it was produced). At that time, two California plants flourished: the one at Trona, built by the American Trona Co., and another one at Borosolvay, 5 km south of Trona, built by the Pacific Coast Borax Co. and the Solvay Process Co.

By 1920, however, World War I had been over for more than a year and the potash price had returned to prewar levels. The plant at Borosolvay was closed; the American Trona Co. plant at Trona managed to survive and undertook a long-term program of basic research. Within the next few years, many of the technical problems were solved and the plant was taken over and renamed by the American Potash & Chemical Co. (AP&CC).

Over the next few decades, lithium (Li), phosphate (PO_4), and bromine (Br) were added to AP&CC's list of products, although production of these stopped later during the late 1900s. At the Westend Chemical Co. plant, 6 km south of Trona and adjacent to the West End settlement, production of borax and potash was started in the early 1920s, but the process was found to be inadequate. However, engineering improvements to the plant put soda ash back into production by 1927, borax was added in 1930, and salt cake (sodium sulfate) was in production by 1955.

Since those times, several changes in ownership and procedures at both plants have taken place. In the late 1900s, another plant was built by AP&CC just southwest of Trona, the ownership of much of the land on the lake was consolidated, and many changes in the operational processes were put into effect (Smith, 1979, p. 5). By the late 1980s, three large industrial-chemical plants, owned by the North American Chemical Co., were pumping brines from beneath the surface of the dry lake and extracting soda ash, potash, borates, and salt cake. Production in 1986 was valued at $172 million (Kerr-McGee Corporation, 1986, p. 24); total production since 1872 exceeds $3 billion (Smith, 1990).

The geologic origin of Searles Valley was as a product of downwarping during late Cenozoic time. Seismic and gravity studies provide evidence of a bedrock floor that is in the form of a synclinelike trough, oriented north-south beneath the Cenozoic sediments (Mabey, 1956, fig. 5). The basin is asymmetrical, and the deepest part is estimated to be about 1,000 m below the east-central part of the present lake surface (in secs. F25 and G30—see pl. 1 for locations). Core KM-3, drilled at the common corner between secs. F22, 23, 26, and 27, penetrated bedrock at 915 m (Smith and others, 1983, table 2), a depth that compares favorably with the geophysical estimate of bedrock depth of about 800 m at that site (Mabey, 1956, fig. 5). There is also evidence of presently active synclinal folding in the basin (Smith and Church, 1980, p. 528-529; Smith and others, 1983, p. 16).

Furthermore, known late Cenozoic faults in the area fail to provide an explanation for the valley's existence. With the exception of the Garlock Fault, a left-lateral fault that trends east-northeast along the valley's south edge, major high-angle faults of late Cenozoic age do not bound the valley. No frontal faults are known in the Argus Range, on the west side of the northern valley (pl. 1). Frontal faults in the Slate Range, on the east side of the valley, are mostly of early Cenozoic or pre-Cenozoic age, except for fault displacements of a few meters that have created a graben, which extends northward as a normal fault (Smith and others, 1968, pl. 1). Normal faults of Quaternary age along the southeast side of the Spangler Hills extend only about half the mapped length of that side (pl. 1), and they do not appear responsible for major displacements. Uplift of the Lava Mountains, south of Searles Valley, may be partly a result of Tertiary activity along the left-lateral Garlock Fault (pl. 1), but its late Quaternary deformation is expressed as upwarping that formed—and is still forming—the northeast-trending Christmas Canyon anticline (Smith, 1964, p. 51-52; Smith, 1991a, fig. 3). The history of earlier geologic studies, as well as the economic development of the area and additional details of the geologic and climatic setting of Searles Valley, are available elsewhere (Smith, 1979, p. 2-8).

Searles Valley has long been recognized as a basin that was filled one or more times by large lakes. Fairbanks (1896, p. 69) first reported shorelines, and Gale (1914) reconstructed the late Pleistocene chain of as many as five lakes, of which Searles was the third (fig. 1*A*). The first lake in the chain was Owens Lake, which received the flow of the Owens River that drained much of the east side of the high south half of the Sierra Nevada, including Mount Whitney (14,495 ft; 4,418 m). Under the present climatic regime, but before irrigation in Owens Valley, Owens Lake was about 13 m deep and covered about half its maximum possible area. During wetter periods of late Pleistocene time, Owens Lake filled and overflowed to the south into Indian Wells Valley to form China Lake. China Lake, in turn, spilled east into Searles Valley, and the two lakes coalesced into one at a level just below that reached by Searles Lake when it filled. In the even more intensely wet periods, Searles Lake overflowed into Panamint Valley, and Panamint, in turn, overflowed into Death Valley. Dramatic climatic fluctuations were responsible for the variations in the numbers and sizes of lakes in this chain, and reconstructing the history of Searles Lake, which was the most sensitive of the basins because it was a perennial but fluctuating lake much of the past 150,000 years, provides a valuable source of paleoclimatic data that is probably applicable to a large region.

As a start in evaluating the history of Searles Lake, an existing 150-ft core hole (L-W), which had previously been drilled by the American Potash & Chemical Corp., was reactivated in 1953 under U.S. Geological Survey (USGS) direction. The core hole was deepened to 875 ft (267 m) and renamed L-W-D. The log of core hole L-W-D was reported in Smith and Pratt (1957). It was also decided that additional shallow coring and a more complete evaluation of all of the upper two saline bodies beneath the surface of the lake were needed.

The additional coring was undertaken during 1954 and 1955 by the USGS in collaboration with the American Potash & Chemical Corp., San Bernardino Borax Mining Co., Ltd., Searles Lake Chemical Corp., and the West End Chemical Co., all of whom permitted additional drilling on their properties. Forty-one core holes, ranging in depth from 29.8 ft (9.1 m) to 143.3 ft (43.7 m), were consequently drilled and logged (Haines, 1959).

In 1967, the Kerr-McGee Chemical Corp., which had absorbed the holdings of the American Potash & Chemical Corp. in 1963, started an exploratory well, KM-3, which was finished in July 1968. Well KM-3 was located at the junction of the four midlake sections 22, 23, 26, & 27, all within T. 25 S., R. 43 E. (township F on plate 1). The core hole recovered lacustrine sediments to a depth of 2,275 ft (693.4 m), alluvial sediments from there to a depth of 3,003 ft (915.3 m), and finally bedrock to a depth of 3,050.2 ft (929.6 m). In September 1968, D.A. McGee, Chairman of the Kerr-McGee Corporation, granted the USGS permission to study these core logs and publish the results (Smith and others, 1983).

The study described in this report is a continuation of these earlier investigations of the subsurface geology of Searles Lake (Smith, 1979; Smith and others, 1983). Those papers document the stratigraphy beneath the surface of the lake as a series of alternating saline layers (indicative of shallow saline or dry lakes) and silts, clays, and marls (indicative of deeper perennial lakes); such sediments constitute the upper 693 m of deposits and represent the past 3.2 m.y. (see fig. 1*C*). Much of the emphasis in the above-cited reports was on the paleoclimatic significance of the fluctuations recorded by the subsurface sediments, but the depths of water in Searles Valley could only be estimated from criteria that allow the salinity of the lake to be inferred.

The present study attempts to reconstruct actual lake levels by tracing lacustrine sediments deposited in lakes of known succession (and approximated ages) to their highest levels in the valley. Conversely, intervening periods of lake recession or

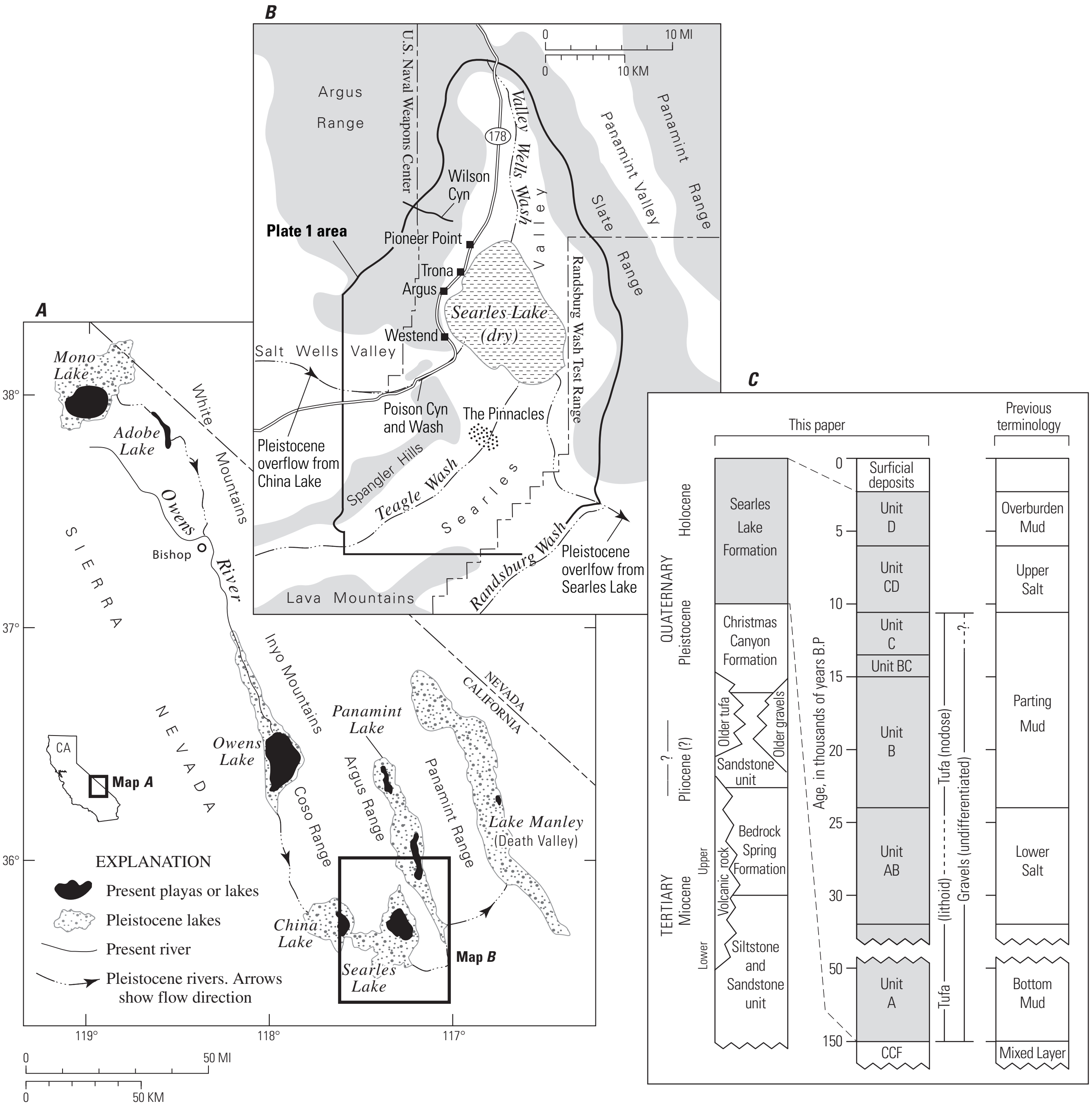


Figure 1. Geographic and stratigraphic setting of Searles Valley and its late Cenozoic deposits. *A*, Map showing locations of Pleistocene and present lakes, playas, and rivers in the northern part of the Great Basin within California. Major mountain ranges are also shown. *B*, Map of the Searles Valley area, showing mountains, canyons, main washes, towns (black squares), and the area of geological mapping on plate 1 (within heavy line). *C*, Generalized stratigraphic column for the late Cenozoic deposits of the Searles Valley area, with expanded columns for the Searles Lake Formation, showing unit names used or defined in this work and equivalent older terminology based on drill cores beneath the surface of Searles (dry) Lake (see Smith, 1979).

desiccation are reconstructed by determining the lowest elevations of interbedded alluvial deposits and fossil soils that are indicative of subaerial conditions. Although the prime emphasis of this study has been placed on the late Quaternary deposits exposed in Searles Valley, studies have also been made of the older Quaternary and Tertiary sediments and rocks exposed near the valley. Pre-Tertiary rocks are not differentiated.

Acknowledgments

I would like to thank the many U.S. Geological Survey (USGS) employees who helped during so many stages of this project. I am particularly grateful to Robert J. McLaughlin for his full-time help in the field and laboratory during the early stages of this study, to Gloria Harris for her nearly full time assistance in the laboratory and office for so many months during the later stages, and to Michele Ono for her careful typing of the final draft of this report. Stacey Andrews, David Aquino, Diane Cheney, Joshua Delgado, Daniel Dilling, Susan Howell, Peter Irish, Michele Ono, Susan Orr, Tammy Parker, Glendora Payton, Jacqueline Richy, Jose Rivera, Rossana Torres, and Ron Valine also assisted in X-ray diffraction, sediment-size analysis, map coloring, table compilation, manuscript preparation, and other tasks. The managers and assistants of the ^{14}C and U-series dating laboratories deserve special thanks for their essential contributions.

Discussions with Charles B. Hunt and Roger B. Morrison during the early stages of this work and with Larry Benson and Richard L. Hay during later stages were helpful in bringing this project to a successful conclusion. Joseph P. Smoot and Robert S. Thompson provided helpful reviews. At the time, all but Hay were with the USGS.

Ronald G. Blom, of the Jet Propulsion Laboratory, Pasadena, California, arranged for access to the false-color satellite photograph of the Searles Valley area that is used for the cover of this volume. Several employees of the chemical companies operating in Searles Valley assisted me in various ways when I was doing field work, especially D.S. Arnold, C.F. Cowie, P. Cortessis, L.J. Czel, F. Dluzak, W.A. Gale, D.E. Garrett, D.A. Holmes, L.E. Mannion, and J.F. Phillips.

USGS editorial assistance and map preparation were provided by Richard Koch, Joel Robinson, Sue Mayfield, Julia Thomas, Jan Zigler, and Peter Stauffer. Manuel Nathenson provided guidance and editorial assistance during final production.

Finally, I would like to thank the 300-or-so participants of two Friends-of-the-Pleistocene field trips, plus several smaller groups who joined me in Searles Valley. They offered critical scrutiny of, and asked probing questions about, my interpretations of the field evidence.

Field and Laboratory Methods

Approximately 600 days were spent in the field compiling the six geologic maps that are the primary basis for this report (pls. 1-4). The first period of field work extended from 1961 to 1970, the second from 1983 to 1996. Mapping was originally compiled on prints or enlargements of black-and-white aerial photographs selected from six sets, none of which covered the entire area or were at the same scale. The mapping on photographs was transferred, using a projector, to enlargements of the topographic base taken from the appropriate 15-minute topographic map.

The base map covering most of Searles Valley (pl. 1) was made by joining four 15-minute quadrangles (Trona, 1949; Manly Peak, 1950; Searles Lake, 1949; and Wingate Pass, 1950) along the edges and then enlarging the combined map from the original 1:62,500 scale to 1:50,000 scale. For the detailed maps (pls. 2-4), these topographic bases were enlarged to 1:10,000 scale. For convenience, the area covered by each of these five detailed maps has been named after included (or nearby) geographic features: Valley Wells Wash (an informal name) (pl. 2*A*), Randsburg Wash (pl. 2*B*), Poison Canyon (pl. 3*A*), Salt Wells Valley (pl. 3*B*), and The Pinnacles (pl. 4).

The extreme enlargement required to make these five detailed maps has reduced the accuracy and topographic detail far below normal levels for base maps. In transferring the geology from photographs to the topography of plates 2 to 4, therefore, compromises were made. In some instances, the geology plotted on photographs was adjusted so its geometry correctly fit the contours as represented by the enlarged maps. In other instances, however, where details of the actual geologic configurations are important to the correct interpretation or would aid another field observer to locate and identify certain outcrops, the generalized contours were ignored and the more detailed field relations, as mapped on the photographs, were plotted.

Many of the units plotted on the geologic maps are too thin or small to be shown accurately, even on the large-scale maps. No minimum thickness was established for mapping, and in some areas, units less than a meter thick were plotted because they are relevant to the interpretation of the lacustrine and nonlacustrine depositional history of the valley fill. Besides the large number of relatively thin units, many of the best exposures and significant relations are observed on steep slopes where even thick units are difficult to plot accurately. The geologic maps in these areas, therefore, are diagrammatic, and future observers in the field will need to adapt to these portrayals.

As the contours on these base maps indicate feet above sea level, all references to elevations in the text are in feet, sometimes followed by appropriate metric equivalents. Horizontal distances, however, are mostly in kilometers, thicknesses of units or stratigraphic sections are in meters, and all other dimensions are in the convenient metric unit.

With the exception of the volcanic rock unit, all of the mapped units of Cenozoic age are chemical or clastic deposits. Because a central focus of this study has been to reconstruct past climates, chemical and clastic deposits indicating lacustrine deposition, which required a wet ("pluvial") climate relative to the present, are generally noted and separated from deposits indicating subaerial deposition, which required a dry ("interpluvial") climate. Criteria for separating the two environments of deposition are many. Discussions and summaries by Clifton (1973) and by Rigby and Hamblin (1972) include many of the criteria used in this study. These and other criteria developed during this study are summarized in table 1.

To simplify the process of describing localities that offer especially good exposures, complete sections, or definitive geologic relations, the townships that are partially or entirely included on the map of Searles Valley (pl. 1) have been assigned capital letters, A through P, as shown on plate 1. Townships L, M, O, and P are actually unsurveyed, but their boundaries have been projected from surrounding grids and hypothetical sections plotted within them. The northernmost partial township, A, is T. 23 S., R. 43 E.; the southeasternmost partial projected township, P, is T. 28 S., R. 44 E. (Mount Diablo Base and Meridian). Sections retain their normal numbers. Thus a locality in section 27, T. 27 S., R. 42 E. would be referred to as "sec. K27." For more precise identifications of locations, especially on the large-scale maps (pls. 2-4), each section is subdivided into sixteenths, which are assigned lower-case letters, as also shown on plate 1 (lower-case i and o are omitted). A locality in the southeast corner of section K27, therefore, is designated "K27-r."

Stratigraphic sections (appendix 1) were measured by a combination of hand-leveling methods and visual estimates of each component bed. Rock and sediment descriptions used in these tabulations and in the text were based on megascopic properties plus hand-lens study; a few thin sections were studied with a petrographic microscope, but they added little information that was useful. Reported occurrences of megascopic crystals of halite, gypsum, and gaylussite were visually identified in the field; identifications of the fine-grained minerals such as calcite, aragonite, dolomite, thenardite, thermonatrite, ulexite, halite, and analcime are based on X-ray diffraction data. Numerical data on sediment sizes (appendix 2) are based on field measurements and laboratory analyses using standard-mesh sieves. Clastic size terminology follows Wentworth (1922). Colors indicated by alphanumeric expressions are based on the Rock Color Chart of Goddard (1951). All carbon-14 (^{14}C) dates are reported without any corrections

Table 1. Criteria used in Searles Valley to differentiate between outcropping lacustrine and alluvial deposits.

Characteristic	Lacustrine Deposits	Alluvial Deposits
Bedding	Persistent; if horizontal, usually for more than 10 m	Lenticular, rarely persist for more than 3 m
Sorting (gravel)	Well sorted, largest fragments commonly about 2x average fragment, none much larger; matrix commonly half sand, half open space, rare clay-size material	Poorly sorted, large fragments may be 100x average size, commonly one or two fragments in a given outcrop even larger, matrix is nearly 100 percent sand and silt, always some clay-size material
Sorting (sand)	Well sorted, some deposits have small percentage of similarly sized pebbles, none large, rare clay-size material	Poor to fair sorting, usually some pebbles having diverse sizes, common clay-size material
Sorting (silt and clay)	Well sorted	Rarely found
Rounding (coarse deposits)	Subangular to well rounded, but individual deposits mostly composed of similarly rounded fragments	Mixture of angular to well-rounded fragments derived mostly from older coarse lacustrine deposits
Fabric (coarse deposits)	Tabular or elongate fragments commonly aligned in persistent "shingle-structure" zones	Tabular or elongate fragments locally aligned in "shingle-structure" zones, more commonly randomly oriented
Fossils	Common, locally abundant, especially in Poison Canyon area	None (except reworked specimens)
Porosity (apparent)	High (little fine material in matrix)	Low
Color (fresh surface)	Fine-grained deposits are light shades of green, gray, or tan; coarse deposits may be gray to very dark gray	Fine deposits mostly tan; coarse deposits dark brown or gray
Color (weathered surface)	Very light tan to tan orange if fine; dark browns to gray if gravel	Tan to dark brown or orange brown
Carbonate content	High throughout	High in soil zones; low elsewhere
Resistance to erosion	Fine-grained deposits with high percentage of $CaCO_3$ very resistant, coarser deposits less resistant, form steep to intermediate slopes	Variable, but generally form intermediate slopes

for initial nonequilibrium conditions in the lake water or for past variations in cosmic ray intensity.

Some abbreviations are used in this report. Dates and geologic ages are expressed in years (yr), thousands of years (ka), or millions of years (Ma); the "ago" and "B.P." suffixes are omitted. Periods lasting thousands or millions of years are abbreviated k.y and m.y. Abbreviations used for metric and English measurement systems are the conventional ones. Sections (sec.) refer to the land-grid system discussed above. Measured sections (meas. sec.) refers to the stratigraphic descriptions in appendix 1.

Stratigraphy and Lithologies of Mapped Units

Three of the rock units discussed herein and shown on the geologic maps (pls. 1-4) are formally designated formations; the Bedrock Spring and Christmas Canyon Formations were established and described elsewhere (Smith, 1964, p. 15-23, 40-42), and the new Searles Lake Formation is described herein. All three of these formations contain a variety of rock types representing both sublacustrine and subaerial sedimentation, and one also contains volcanic deposits; formal stratigraphic terminology would now designate each of them as an "alloformation," to emphasize their diversity. However, the first two were published before the introduction of that term, and the third is no less diverse, so the term "Searles Lake Formation" is used herein. The other rock units are informal units whose lithologies, stratigraphic positions, or surface morphologies generally allow them to be identified and differentiated with little difficulty.

Detailed stratigraphic study was limited to the late Quaternary lacustrine (and interbedded alluvial) sediments of the Searles Lake Formation of late Pleistocene to late Holocene ages. These lacustrine sediments have limited elevation ranges, from the floor of the valley (1,616 ft) to about 2,280 ft; geologic relations among late Cenozoic deposits exposed above this latter elevation were studied less carefully. Similarly, sediments assigned to the Christmas Canyon Formation and to units that are contemporaneous or older were also studied in less detail because of their ages, but descriptions and observations of stratigraphic successions of these older sediments were made in sufficient detail to determine the environment of deposition and the areal extent of the unit. Subdivision of these older units into members or subunits was generally not attempted, but the Christmas Canyon Formation of middle Pleistocene age is divided into lacustrine and alluvial facies. The Searles Lake Formation was divided into 12 units on plate 1 and as many as 27 units and subunits on plates 2 to 4. Younger deposits of middle and late Holocene ages are subdivided into five units.

Rocks assigned to Tertiary units are mostly deformed. In areas along the Garlock Fault, rocks assigned to the siltstone and sandstone map unit dip steeply and may be locally overturned, but the other two Tertiary rock units are not as extensively deformed within the mapped area. Some of the sediments assigned to the Tertiary or Quaternary units are deformed, but typical dips are between 10° and 20°. Sediments assigned to the middle Pleistocene Christmas Canyon Formation are slightly deformed, dips being mostly in the range of 2° to 5°. The Searles Lake Formation may have undergone regional uplift of a few meters, but tectonic tilting is not measurable.

The regions covered by plates 2 through 4 required about 300 days of field work. The areas on plate 1 not covered by those more detailed maps required several hundred additional days. The major difficulties in mapping such a large area over a period of more than 30 years were (1) applying uniform criteria to the identification, correlation, and mapping of units and (2) making retroactive adjustments to existing mapping as new units were identified or old units redefined. Some errors were undoubtedly introduced or not eliminated as a result this process, but every effort was made to reduce those to a minimum.

Three areas on plate 1 represent significantly less detailed geologic mapping, and two areas are based largely on previously published mapping. Except for the area shown on plate 2*B*, the region within the Randsburg Wash Test Range (part of the Naval Weapons Center, fig. 1*B*), near and southeast of the Garlock Fault and east of Christmas Canyon, reflects only a few days of reconnaissance mapping. Units shown as mapped on the U.S. Naval Weapons Center near the west edge of plate 1, west of Searles Lake and north of Salt Wells Valley (fig. 1*B*), are based on photogeology. The geology of the floor of northern Searles Valley above 2,280 ft is based on reconnaissance mapping. The geology of the west edge of the Slate Range is modified from Smith and others (1968, pl. 1); the geology of the northern Lava Mountains is modified from Smith (1964, pl. 1).

Tertiary Units

Three rock units in the Searles Valley area are known or assumed to be of Tertiary age. Vertebrate fossils in the Bedrock Spring Formation (Smith, 1964, p. 15-23) are of Hemphillian age (C.A. Repenning, oral commun., 1985), which is presently considered to be latest Miocene. Stratigraphic evidence shows most volcanic rocks in the Lava Mountains to be younger than the Bedrock Spring Formation, but the volcanic rocks in the Argus and Slate Ranges could be older or younger than that formation. The siltstone and sandstone unit, which crops out near the Garlock Fault, as shown in the southern part of plate 1, is probably older than the Bedrock Spring Formation inasmuch as it is somewhat more indurated and much more intensely deformed, but the two units are not known to be in stratigraphic contact.

Siltstone and Sandstone

Rocks of this (unit Ts) were described briefly by Noble (1931) and by Smith and others (1968, p. 14), who concluded that they had a lacustrine origin and tentatively correlated them with the Christmas Canyon Formation, following the suggestion of Smith (1964, p. 41, fig. 17). During the present study, more detailed mapping of the relations east of the type section of the middle Pleistocene Christmas Canyon Formation, which is mostly of lacustrine facies, shows that the sediments constituting the type section rest unconformably on the fine-grained lacustrine deposits of the early Miocene(?) siltstone and sandstone unit (pl. 1). The lithologies of the two units here are similar and the contact between them is not exposed, but in outcrops less than 100 m apart, contrasts in the degree of induration and the steepness of their dips leave little question that they are different. Furthermore, in many areas the gravel and sand facies of the Christmas Canyon Formation rests unequivocally on the deformed lacustrine deposits of the siltstone and sandstone unit.

Within the area of plate 1, the rocks of this unit (Ts) are restricted to areas just north and south of the Garlock Fault. Most are well-bedded siltstone and sandstone, commonly containing thin layers of well-sorted gravel, characteristics that support a lacustrine origin. Beds, typically 0.5 to 1.0 m thick, dip at angles as high as 90°. Colors of well-exposed sections are grayish yellow (5Y7-8/2-4), although coarser facies just east of the mapped area are characterized by darker shades of tan and brown. Noble (1931, p. 10-13) reports gypsum and traces of nitrates in these deposits, possibly an explanation for the fact that little vegetation grows on outcrops of the finer grained facies of this unit. Several tuff beds were noted.

Beds of unit Ts are deformed in almost every exposure, with dips exceeding 45° being common (fig. 2). No pattern of fold axes or faults was determined, nor were any stratigraphic sections measured. However, much more extensive sections crop out to the east of the area of plate 1, along the south edge of the Slate Range (Smith and others, 1968, pl. 1), where the rocks of this group could have thicknesses that exceed 500 m. Deposits in other areas that are similar and possibly correlative are not known.

No fossils have been found in this unit, and none of the volcanic ash layers have been correlated with dated ash layers. Its age, therefore, is not known, but it is reasonable to assign it a Miocene(?) age.

Figure 2. Deformed Tertiary siltstone and sandstone beds (unit Ts) unconformably overlain by horizontal beds of unit A of the Quaternary Searles Lake Formation. The tilted lacustrine deposits, of possible early Miocene age, here dip about 55° (apparent dip in photograph about 40°). Sublacustrine erosion formed a flat, unchanneled surface before deposition of unit A lacustrine beds. View toward west; location: plate 1, sec. M19-k.

Bedrock Spring Formation

Outcrops of the Bedrock Spring Formation (unit Tbs; Smith, 1964, p. 15-23) are all south of the Garlock Fault. Its clastic rocks are chiefly arkosic alluvial sandstone and conglomerate that are light pinkish tan. In the 1,500-m-thick type section, which is about 3-6 km south of the southwest corner of the mapped area of plate 1, lacustrine layers are found in the lower quarter and near the top, as well as scattered in other parts of the formation. Alluvial gravels make up most of the rest. The debris was largely derived from plutonic terrain to the south, although volcanic rock fragments are found in nearly all exposures and volcanic breccia layers are prominent locally. Reconstruction of the depositional basin for this formation suggests that its north edge was parallel to the Garlock Fault and just north of the outcrops shown on plate 1 (Smith, 1964, p. 19, fig. 9).

Vertebrate fossils, which include six identifiable genera from 24 sites, indicate a Hemphillian age, which was once considered early to middle Pliocene (Smith, 1964, p. 21) but is now considered to be of uppermost Miocene age (C.A. Repenning, oral commun., May 1985).

Volcanic Rock

Volcanic rock (unit Tv) crops out in two areas shown on plate 1. Near the north tip of the mapped area, flows of black to dark gray basalt rest on the flanks of the Argus and Slate Ranges (Smith and others, 1968, p. 14; Smith and Church, 1980, fig. 4). Augite-olivine basalt dominates these rocks, but basaltic andesite is also reported (Moore, 1976, p. 68, 69). Flow thicknesses within the area of plate 1 are most commonly between 30 m and 60 m. Ages of these volcanic rocks are uncertain. The nearest radiometric age on similar rock, 5 km west of the northwest corner of the area shown on the plate 1 base map, is 1.75±0.10 Ma (Duffield and Bacon, 1981, loc. 60). The basaltic rocks shown on the northern part of plate 1, however, are believed to be older because of the evidence that they predate development of the Argus-Slate Range Syncline and Slate Range Anticline (Smith and Church, 1980, p. 528-529, figs. 1 and 4). That syncline has since been recognized as the probable cause of Searles Valley and as extending southward to near the Pleistocene outlet of Searles Lake, so it was renamed the Searles Valley Syncline (Smith, 1991a, p. 615). Alluvial sedimentation in Searles Valley is known to have begun well before deposition of the first lake deposits at 3.2 Ma (Smith and others, 1983, p. 16). Radiometric ages of basaltic rocks on the crest and east flank of the northern Argus Range, in the vicinity of Rainbow Canyon, which is 40 km north of the area of plate 1, range from 7.7 to 2.5 Ma (Schweig, 1984, table 1); the older half of this age range seems more reasonable for these flows.

The majority of the volcanic rocks that crop out near the south edge of the area shown in plate 1 are well indurated, massive lapilli tuff and tuff that form variegated, steep-sided hills (Smith, 1964, pl. 1, p. 39-40, 42). They appear to rest on Bedrock Spring Formation, but relations are obscure. Included in this unit on plate 1 are several younger northeast-trending basalt dikes and small flows; they appear to intrude the Christmas Canyon Formation, which would make them Quaternary in age, but the field relations are also obscure.

Tertiary or Quaternary Units

Sandstone and Siltstone

Most of the rocks assigned to the sandstone and siltstone (unit QTs) crop out in two parts of the area of plate 1, but there is no stratigraphic evidence that they are correlative. The rocks cropping out in the Spangler Hills, which are found at elevations as much as 140 ft (43 m) higher than any deposits of the Searles Lake Formation, are poorly exposed but characteristically form very light gray outcrops. They are uniformly arkosic and include both alluvial and lacustrine deposits. Fragments range from angular to round and their sizes vary from medium sand to pebble gravel. Granitic rocks, like those in the Spangler Hills, make up most of the coarser detritus. Many outcrops have a well-developed layer of caliche near or at the surface, and a pronounced lag gravel characterizes most surfaces.

Ages for these rocks are uncertain. They appear to underlie the older gravel (unit og) of Pliocene or early to middle Pleistocene age (defined below), although contacts are poorly exposed. A greater age is also suggested by the caliche development, which is more extensive than in the older gravel. Where these deposits are in contact with the sediments mapped in the Spangler Hills as early units of the Searles Lake Formation, the greater concentrations of caliche distinguish the older deposits. If the deposits represent a very much earlier stand of Searles Lake than the younger stands discussed in this report, that lake's surface and the lake's outlet would have had to be higher than during late Pleistocene time or the Spangler Hills lower.

Rocks assigned to this unit that crop out near the southeast corner of the area of plate 1 are also both lacustrine and alluvial in origin. North of the Garlock Fault, virtually all rocks assigned to this unit are lacustrine. South of the fault, most of the rocks assigned to this unit are alluvial; an interbedded facies that may be lacustrine is not similar to the lacustrine deposits included in this unit just north of the fault.

The lacustrine deposits just north of the Garlock Fault are mostly well bedded, coarse to fine sand with interbedded silt. Characteristically, these rocks are well indurated and beds are 2-10 cm thick. A typical sand layer is composed of medium- to fine-grained angular sand containing some angular pebbles; about 80 percent of the grains are granitic debris and 20 percent are volcanic debris. Colors of fresh surfaces of sandstone outcrops are commonly olive-yellow hues in the range 5Y4-7/1-2. Siltstone outcrops are slightly lighter. Good outcrops of these rocks can be found in sections L26-p and L25-q (pl. 1) and M19-l (pl. 2*B*). Geologic relations consistently show that these rocks unconformably underlie sediments of the

Christmas Canyon Formation and unconformably overlie the siltstone and sandstone of Tertiary age.

The alluvial and lacustrine deposits assigned to this unit south of the Garlock Fault were not carefully mapped or studied. Most good exposures are close to the Garlock Fault, where the beds are tilted and deformed. A kilometer or more south of the fault, they are poorly exposed except along the sides of Randsburg Wash; there (sec. P5-f), 3-5 m of exposed sediments consist of moderately indurated, pebbly arkosic sand that is pale brown (5YR5-7/2). Poorly sorted, subangular to subrounded volcanic rocks constitute the coarser fragments. Another well-exposed surface (sec. M33-c) consists of grayish orange (10YR7/4) pebbly arkosic sandstone that is faintly bedded.

These rocks are similar to the sandstones and conglomerates of the upper Miocene Bedrock Spring Formation in the Lava Mountains (Smith, 1964, p. 17-18), and the possibility exists that the rocks of this sandstone unit in this area are extensions of that formation. The rocks south of the Garlock Fault assigned to this sandstone unit are clearly overlain by the gravels and lacustrine facies of the Christmas Canyon Formation, and they are underlain by the Tertiary siltstone and sandstone unit. These rocks are not correlated with the Bedrock Spring Formation, however, because they are less deformed and indurated than the rocks of that formation.

Sediments questionably assigned to this unit crop out unconformably beneath gravels of the Christmas Canyon Formation along the south edge of the Spangler Hills (secs. K31-p and N6-c). They are composed mostly of tan sand that contains many calcareous pods and gypsum crystals (altered to bassanite). Several interbedded gravel lenses, about 1 m thick, are composed of light-purple or banded light-tan volcanic lavas and greenish or white pyroclastic rocks, components known from their mineralogy and petrographic textures to have been derived from the Lava Mountains and Summit Range 10 km to the south and southwest (Smith, 1964, pl.1, p. 27-40). This suggests their deposition in a north-sloping fan at some time prior to uplift of the Spangler Hills.

Older Tufa

Ten or more large tufa mounds (unit ot) crop out in the south quarter of Searles Valley; two small masses were tentatively identified in the northern valley (secs. C5 and C8). In the southern part of the valley, the largest tufa mound covers an area of 0.2 km^2 and the highest extends 37 m above its base (fig. 3). This massive lithoid tufa, following the terminology of Scholl (1960, p. 418-419, figs. 3c and 10), is lithologically distinct from the light tan to brown, porous tufa masses deposited during the time represented by the Searles Lake Formation, although most outcrops of massive lithoid tufa have coatings of younger tufa on their outer surfaces.

The massive lithoid tufa consists of dense calcite that has weathered with the development of sharp ridges and points that are attributed to solution by rain. Exposed surfaces are

Figure 3. Two dark hills, about 1.5 and 3 km from camera, are mostly composed of older tufa, with tufa of Searles Lake Formation locally coating the older deposits. Nearest large hill is about 37 m high and 0.5 km wide; note shorelines eroded into surface. Railroad tracks visible on near side of hill. Symmetrical flat-top peak on skyline is Pilot Knob, about 35 km from camera. View to southeast; location of largest tufa mass: plate 1, sec. K24-c.

light olive gray (5Y6/1) to medium gray (N5-6); fresh surfaces are yellowish gray (5Y7-8/1-2) to pinkish gray (5YR7-8/1-2). Locally, medium to coarse sand is embedded in the calcite matrix, but some samples are virtually pure calcite. Cavities and drusy fillings are present, but they are much less abundant than in the tufa types associated with the Searles Lake Formation. Scholl (1960, p. 419) reports the bulk density of this massive lithoid tufa as 1.9. Pure calcite has a density of 2.7, indicating that the measured samples of this older tufa have about 30 percent porosity.

The restriction of massive lithoid tufa to about the same elevation range as the lacustrine sediments of the Searles Lake Formation suggests a sublacustrine origin. The dome-like shapes and the alignment of three groups of these masses (secs. K14, K24, L19, and L29 on pl. 1) suggest an origin related to springs aligned along a buried fault at right angles to the mapped faults in this area. Springs could have introduced Ca- and HCO_3-rich water into the slightly alkaline lake, causing precipitation of calcite inorganically when the two waters mixed and the solubility product of calcite was exceeded. The other tufa masses are not aligned with each other or with known faults; the characteristic they have in common is that they lie at or near the highest shorelines of the later lakes, arguing for an organic process that included the action of algae in shallow water, where the penetration of sunlight was strongest.

Sediments and tufas associated with the Searles Lake Formation are all stratigraphically younger than the older tufa. That both these map units are restricted to the same elevation range implies that there was not sufficient geologic time for tectonic forces to have greatly altered the basin configuration and suggests that the older tufa deposits are not much older. A U-series age of “greater than 300,000 ka” (J.L. Bischoff, written commun., March 28, 1984, lab. no. 84-19a), however, indicates that the older tufa deposits are at least twice a old as the Searles Lake Formation.

Older Gravel

North of the area where the Searles Lake Formation is underlain by the gravel facies of the Christmas Canyon Formation, essentially the latitude of The Pinnacles (pls. 1 and 4), all alluvial gravels that underlie that formation are included in the older gravel unit (og). In most places, they are cobble to boulder gravels with poorly sorted, gray to tan sand constituting 50 to 80 percent of the sediment and angular to subangular pebbles, cobbles, and boulders constituting the balance. Locally, within a kilometer of the edges of the Argus and Slate Ranges, boulders a meter or more across are incorporated. Bedding is generally poor and discontinuous; some cross-bedding was observed. Most outcrops along the sides of canyons are very well cemented with calcite.

Deposits in separate areas may differ significantly in age. Even deposits that are physically overlain by tufa or sediments assigned to the Searles Lake Formation appear in some instances to be demonstrably older than the base of that formation; prior to deposition of the younger sediments, channels were cut into some of the top surface of the older gravel, and moderate to strong soils as much as 2 m thick were developed. The channels may only document a limited depositional gap, but the soils probably document exposure to weathering for tens of thousands of years after gravel deposition ceased. Slight angular discordances are observed but are uncommon.

Deposits mapped as part of this unit near the west edge of the area of plate 1, in and near the areas of plates 3*A* and 3*B*, are also angular cobble and boulder gravels. Plutonic and hypabyssal rocks are the most abundant fragment types in these areas. The gravels are not as indurated as are gravels in some other parts of the valley, and the cobbles and boulders mostly have a heavy coat of desert varnish. In the Poison Canyon area (pl. 3*A*), the older gravel unit has been separated into two facies on the basis of stratigraphic position and the intensity of varnish and soil development. The older facies is a boulder gravel that is very dark gray to brown and heavily varnished, and a strong calcareous soil has been developed on its surface. The younger facies is a pebble gravel that is dark orange-brown and less heavily varnished, and its angular fragments in a sandy matrix suggest a colluvial or debris-flow origin. Inasmuch as both facies extend to the ridge of this part of the Spangler Hills, and are therefore considered to be of approximately the same age, some process has apparently retarded the varnish process on the lighter colored facies, even though both include the same rock types. Field study did not resolve this question.

The older gravel that rests on bedrock in the Slate Range, northeast of Searles Lake, was described by Smith and others (1968, p. 14) as having a thickness of as much as 120 m. Its lithology is similar to those described above, and it forms a discontinuous cover over Manly Pass, a broad saddle in the Slate Range having a maximum elevation of nearly 2,900 ft (885 m). In an area east of the north edge of Searles Lake, the older gravel can be traced down to elevations where it is cut by shorelines and overlain by sediments of the Searles Lake Formation. The great thickness of gravel included in this unit in the Slate Range, and its position on the crest of the range, suggest that a substantial amount of time is represented, and the lower part—or all—of this section could be of Tertiary age.

Exposures of older gravel along two canyons in the Slate Range (secs. G10-n, G15-c,d,e,g,l, and G16-h) reveal three or four thin zones of lacustrine sands and gravels. One zone, 1 to 2 m thick, is near the top of the section and is composed mostly of angular gravel (sec. G15-l). The middle zone generally consists of two beds of lacustrine gravel, each 1 to 2 m thick and separated by 1 to 2 m of alluvium; another bed lies lower in the section (measured sec. G10-n). Some layers are very coarse sand, but most are gravels that are dark gray, poorly sorted, and composed mostly of subrounded to rounded, cobble-size fragments, with foreset and backset bedding locally prominent. A discontinuous volcanic ash layer (sec. G16-h) is approximately at the level of these beds, but it proved unsuitable for K/Ar dating. Study by Ray Wilcox of the USGS found it to be unlike the Lava Creek or Bishop ashes, and he was unable to correlate it with other ashes of known age (written commun., August 1967).

The older gravel map unit is probably correlative in part with the Christmas Canyon Formation. The two units are as similar as the rocks in their diverse source terrains allow, implying a similar climate at the times of their deposition. Both contain a lacustrine facies, and both have strong calcic soils, 1 to 2 m thick, developed on their upper surfaces. My inclusion of the deposits on the crest of the northern Slate Range in this map unit, as well as the numerous coarse gravel outcrops elsewhere in the mapped area that lack stratigraphic control, is responsible for the expansion of the suggested age for this unit from Pleistocene down into the Pleistocene-or-Pliocene age bracket (see pl. 1, Description of Map Units).

Christmas Canyon Formation

The Christmas Canyon Formation was established by Smith (1964, p. 40-42) on the basis of outcrops in the Lava Mountains to the south of Searles Valley. Two facies, one a lacustrine sandstone facies and the other an alluvial boulder conglomerate facies, were described. The type section (sec. O8-e) is about 45 m thick. It is composed predominantly of nearshore lacustrine siltstone, sandstone, gravel, and breccia, although the alluvial boulder conglomerate facies accounts for the uppermost 6 m and a 10-m bed of gravel within the lacustrine facies may be alluvial in part. The Lava Creek B ash (0.64 Ma) lies 1 m below the top of the lacustrine facies (Izett and Wilcox, 1982; Izett and others, 1992; Lanphere and others, 2002). On plate 1 of this report, the lacustrine facies of this formation is mapped as sand and silt (ccs), and the alluvial facies is mapped as gravel and sand (ccg).

The lacustrine facies grades rapidly from silt and sand in the most northerly exposures (secs. O5-n,p and L23-f) to the interfingering fine-and-coarse lithologies of the type section (Smith, 1964, figs. 14 and 15). Most of the finer facies are tan to grayish yellow sandstone and siltstone, with pebble stringers in some zones. A lacustrine origin for all of these sediments is based on (1) their high content of $CaCO_3$, (2) the persistence of bedding planes, (3) the general lack of fragments that are several times larger than the average sizes in that layer or that exceed 10 cm in maximum dimension, (4) the absence of channels, and (5) the continuity of bedding between unquestioned fine lacustrine layers and the interbedded coarser lacustrine layers. Several zones composed of calcareous tubes and nodules resemble fossil soils, but the absence of channeling of other beds at these levels supports the earlier conclusion that these features are more likely to be zones of calcified water-plant roots (Smith, 1964, p. 42).

The gravel and sand facies of the Christmas Canyon Formation represents more than 90 percent of the exposures of this formation shown on plate 1. In well-exposed sections, which may be as much as 15 m thick, poorly sorted, coarse to very coarse sand constitutes the moderately indurated matrix. This matrix is found in two colors—the more abundant is yellowish brown (10YR6-8/2-4), the less abundant is pale red (10R5-6/2-4). Conflicting evidence was noted as to their stratigraphic sequence; there may be more than one layer of each. Angular to subrounded pebbles, cobbles, and boulders make up 5-50 percent of these rocks (fig. 4). Most pebbles and some cobbles are angular to subangular, but boulders are generally more rounded. A strongly developed calcic soil is found on both exposed and buried surfaces of this unit. It consists of a reticulated network of calcite veins, 2-5 cm thick, that extends downward as much as 2 m. The matrix material is extensively altered to clay. Samples of this clay, from an exposure of the soil where it is overlain by basal beds of the Searles Lake Formation (sec. I32-r), were studied by R.L. Hay, who writes (written commun., March 1989):

> The clay is a green (5GY4/2) illite that meets most of the criteria for glauconite * * *. The tetrahedral sheet in the green illite is almost at the boundary between celadonite and glauconite. The (060) d spacing is 1.514Å, which falls in the range 1.510-1.517 accepted for glauconite, but the Fe/Al ratio is too low. It can be called a glauconitic illite. * * * The green illite is presumably the reaction product of pedogenic clay, most likely montmorillonite, with alkaline pore fluid from overlying sediments [that are lateral equivalents] of the Bottom Mud. Much of the Fe in glauconite is very likely from the isovolumetric alteration of magnetite to porous hematite, which releases considerable Fe to solution.

Additional data on the implications of the $\delta^{18}O$ in these clays was later presented by Hay and others (1991, p. 90).

A diagnostic fragment type in the Christmas Canyon Formation is vesicular basalt that was derived from the Black Hills, 5 to 15 km south of the area of plate 1, and the presence of these fragments was the criterion used in identifying this

Figure 4. Outcrop of gravel facies of the Christmas Canyon Formation. Cobbles and boulders, composed of vesicular basalt and more felsic volcanic rocks, were derived from outcrops 20 km southeast of this locality, which is in sec. L5-r (pl. 1). Geologic pick is 28 cm long.

formation in most areas of plates 1, 2*B*, and 4. Andesitic and dacitic fragments of the types found in the same area further indicate this direction of sediment transport to be correct. This formation, however, has since been deformed into a series of broad folds that trend N. 50° E. and display as much as 100 m of structural relief. This deformation must have occurred during the period since 0.64 Ma, the age of the Lava Creek ash (Smith, 1991a, p. 617-621; Izett and others, 1992; Lanphere and others, 2002), which lies about 1 m below the basalt-rich gravel facies of this formation. The basaltic fragments are characteristically 0.1 to 0.5 m across and concentrated in the lag gravels on outcrops. In southern Searles Valley, gravels of this formation contain basalt fragments throughout an area that extends from the south edge of the area of plate 1 to a line that is a few hundred meters northwest of Teagle Wash. On plates 1, 2*B*, and 4, however, the formation has been extended into two areas where basalt fragments are not included. One extension is on the flanks of the Slate Range east of Randsburg Wash, which appeared justified because both the top and base of those gravels lie on grade with the easternmost basalt-bearing gravels of this formation. The second area is on the southeast side of the Spangler Hills, where the elevations of the top surfaces of the gravels included in this formation can be projected to the same grades as gravels containing basalt fragments.

The lacustrine facies has been correlated with unit D+E in the subsurface section beneath Searles Lake (Smith and others, 1983, p. 17). That unit is a 61-m-thick body composed mostly of calcareous silt and clay representing perennial lakes, but it also includes several salt layers that represent desiccation. The correlation is based in part on the similarity in the radiometrically and paleomagnetically estimated age of 0.57 Ma for the top of that subsurface unit and the 0.64 Ma age of the Lava Creek B ash near the top of the lacustrine facies of the Christmas Canyon Formation at its type section. That correlation allows the gravel and sand facies of the Christmas Canyon Formation, which overlies the sand and silt facies at the type section, to be correlated with the subsurface deposits of unit C of Smith and others (1983), a mostly saline layer representing desiccation of the lake and alluviation throughout the surrounding valley.

Searles Lake Formation

The Searles Lake Formation, a new formation described herein (see table 2 for units and subunits of the formation and their correlation), is the outcropping record of the uppermost 50 to 70 m of sediments known from numerous cores from beneath the surface of Searles Lake, the longest of which is 930 m and extends to bedrock. On the basis of those cores, lacustrine histories have been interpreted for the past 150 k.y. (Smith, 1979, p. 108-112) to 3.2 m.y. (Smith and others, 1983, p. 20-22). It is axiomatic that the history of lake sedimentation based on the subsurface record must be compatible with the history of lake fluctuations derived from the outcropping record.

In selecting the stratigraphic limits of this formation, in an area that has been the site of a lake during much of the past 3.2 m.y., I wished to restrict its time frame to a period that was dominantly lacustrine and young enough for much of its record to be preserved in outcrop. The extensive alluvial gravel of the Christmas Canyon Formation and the older gravel unit clearly represent a long period of low lake levels. The base of the Bottom Mud, which appears to be the product of a deep perennial lake that started filling the basin at 150 ka, is interpreted to be the approximate equivalent of the earliest beds of the well-preserved lacustrine sediments exposed in Searles Valley. The lakes responsible for the sediments immediately beneath the Bottom Mud, units A and B of the Mixed Layer (Smith, 1979, p. 13-15), which represent the interval between about 350 ka and 150 ka, are interpreted to have had depths that fluctuated between about 130 and 170 ft (Smith, 1979, fig. 32, p. 86). A 170-ft-deep lake in Searles Valley, whose floor at that time was near 1,400 ft elevation, would have deposited all of its highest sediments well below the present dry surface of Searles Lake, meaning that none could now be exposed.

The top of the youngest of the perennial-lake sediments in the valley defines the top of the Searles Lake Formation. Correlations between the informally named subsurface units and the formally named units and subunits of the outcropping formation are shown in table 3. As discussed in detail later, most of those correlations are supported by ^{14}C dates, but the most compelling physical evidence is provided by the mapped stratigraphy.

The Searles Lake Formation therefore includes all of the perennial-lake deposits in Searles Valley that overlie the Christmas Canyon Formation and equivalent or older units. Alluvial deposits that are interbedded with these lacustrine deposits, and inferred upslope correlatives of them, are also included in the formation. This formation is divided into seven main units, but in no one place are all of them preserved and exposed. The type section is designated as the outcrops in the Poison Canyon area (pl. 3*A*) that are south of California Highway 178, in section H24-f (figs. 5 and 6). The 11 undeformed beds of the Searles Lake Formation in this 25-m ridge are subunits of only three of the seven mapped units in the formation (Smith, 1987, p. 138-141). Supplemental reference sections are designated as (1) the southwest-facing outcrops in the central part of section H14-r (pl. 3*A*, fig. 7) and the laterally correlative outcrops in the northwest part of section H23-a; (2) the deposits exposed in section I8-n (pl. 3*A*); (3) the sediments exposed in the vicinity of section I30-c (pl. 4, fig. 8); and (4) the western part of section I32-r (pl. 4, fig. 9). These additional sections are described in appendix 1. Together, these five areas provide well-exposed strata representing all of the formation's seven units and many of their subunits.

The seven main units of the Searles Lake Formation were deposited successively; the undifferentiated gravel unit and tufa unit span the formation's entire depositional period. Four of the seven successive units represent times when lakes in the valley expanded significantly, and these are named unit A (the oldest), unit B, unit C, and unit D. Units representing the three

Table 2. Stratigraphic correlations between units and subunits of Searles Lake Formation shown on plates 1-4.

Units of Searles Lake Formation	Units and subunits on plate 1 and larger scale maps					
	Searles Valley (pl.1)	Valley Wells wash (pl. 2*A*)	Randsburg Wash (pl. 2*B*)	Poison Canyon (pl. 3*A*)	Salt Wells Valley (pl. 3*B*)	The Pinnacles (pl. 4)
D	sd					sd
CD	scd			scd		scd
C	sc		sc	sc4		
					sc3c	
		sc3		sc3	sc3b	sc3
					sc3a	
		sc2		sc2	sc2	
		sc1d		sc1	sc1	sc1
		sc1c				
		sc1b				
		sc1a				
BC	sbc	sbc2	sbc	sbc		sbc
		sbc1				
B	sb		sb	sb6[2]	sb	sb6
		sb2[1]		sb5		sb5
				sb4		sb4
		sb1		sb3		sb3
				sb2		sb2
				sb1		sb1
AB	sab	sab7	sab	sab7		sab
		sab6		sab6		
		sab5		sab5[3]		
				sab4		
				sab3		
				sab2		
				sab1		
A	sa	sa		sa		sa4
						sa3
			sa		sa	sa2
						sa1

[1]Subdivision of unit B on plate 2*A* not correlated with individual subunits in other areas.

[2]Only the six subunits in the southeast part of plate 3*A* are correlated with subunits in plate 4.

[3]Subunits sab1 to sab5 in plate 3*A* are correlated with subunit sab5 in plate 2*A*.

Table 3. Subsurface stratigraphy of Searles Lake, inferred lake character, and correlative outcrop units.

[Data from Smith, 1979, p. 108-112; Smith, and others, 1983, p. 16-18]

Subsurface unit	Age[1] (ka)	Inferred character of lake	Outcrop units and subunits (pl. 1)
Overburden Mud	6.0 (?)	Perennial, shallow and saline	Unit D (sd, sdg, sds)
Upper Salt	10.5	Desiccating or dry	Unit CD (scd)
Parting Mud	24.0[2]	Perennial and deep, followed by a shallow stand, then several more brief deep stands	Units C, BC, B (sc, sbc, sb)
Lower Salt	32.0[2]	Alternating deep perennial lakes and small shallow lakes	Unit AB (sab)
Bottom Mud	150[3]	Perennial and deep, brief(?) periods of intermediate lakes	Unit A (sa, saa)
Unit A + B	310[4]	Perennial, intermediate to shallow depths	ccg, og
Unit C	570	Dry, briefly perennial	ccg, og
Unit D+E	1,000	Mostly perennial, intermediate depths	ccs, ot (?)
Unit F	1,280	Perennial, deep	ccs, ot (?)
Unit G	2,040	Perennial, intermediate depths, periodically desiccated	?
Unit H	2,560	Dry, playa	?
Unit I	3,180	Perennial, deep	QTs (?)

[1]Age is for base of unit.

[2]Stuiver and Smith (1979, p.74) estimated these horizons, using ^{14}C methods, to be 24.0 ka and 32.5 ka; Peng and others (1978, table 5) determined average corrected ^{230}Th ages for these horizons of 24.5 ka and 32.0 ka.

[3]Estimated by Smith (1979), by extrapolation of ^{14}C-determined sedimentation rates, to be about 130 ka. U-series age determined by Bischoff and others (1985, fig. 2) may confirm that estimate, but considerations described in text favor the 150 ka age.

[4]Bischoff and others (1985, fig. 2) date this horizon as greater than 0.33 Ma.

intervening periods when the lake underwent partial or complete recession are named with letters assigned to the preceding and succeeding lacustral expansions, namely unit AB, unit BC, and unit CD. With two exceptions, these units represent the maximum practical subdivision of the Searles Lake Formation where mapped at 1:50,000 scale (pl. 1); the exceptions are units A and D, which are divided into two facies on that map. In areas mapped in more detail (pls. 2-4), individual units have been subdivided into as many as seven subunits, using numbers and lower-case letters for successive subdivisions (for example, subunit sc3a). The inferred correlations between subunits in different areas are complex. Some map units assigned the same subunit label are considered correlative, some are not; table 2 indicates which correlations are intended.

The thickness of the Searles Lake Formation varies greatly. Some of the thickest accumulations of individual units or subunits occur where bars formed. Where blanket sedimentation took place, however, the thickest deposits occur in the area of the paleolake that bordered the inlet, where the main volume of water entered Searles Valley from China and Owens Lakes and the Owens River (fig. 1*B*). This region extends from Salt Wells Valley (pl. 3*B*), through Poison Canyon into the area to its east (pl. 3*A*). It was both a "clastic delta," as sediment from upstream drainages flowed into the quiet body of water and settled, and a "chemical delta," as dissolved Ca and HCO_3 entered the basin, mixed with high-pH water of the lake, and precipitated as calcite, aragonite, and possibly dolomite. Parts of the paleolake that received water from major local drainages in the northern and southern parts of Searles Valley (fig. 1*B*) had smaller deltas, and some evidence of more calcareous deposits in these areas is found. Parts of the paleolake that received drainages from single,

Figure 5. Type section of the Searles Lake Formation along south side of Poison Canyon Amphitheater (pl. 1, sec. H24-f; see also pl. 3*A*). The lower 18 m of the section described in figure 6 is along right side of reentrant in lower slope (right arrow); remaining section shown in figure 6 is exposed below skyline in left quarter of photograph (left arrow). View toward south.

short canyons have markedly less chemical component in their sediments, which are composed primarily of sediment from those and nearby canyons.

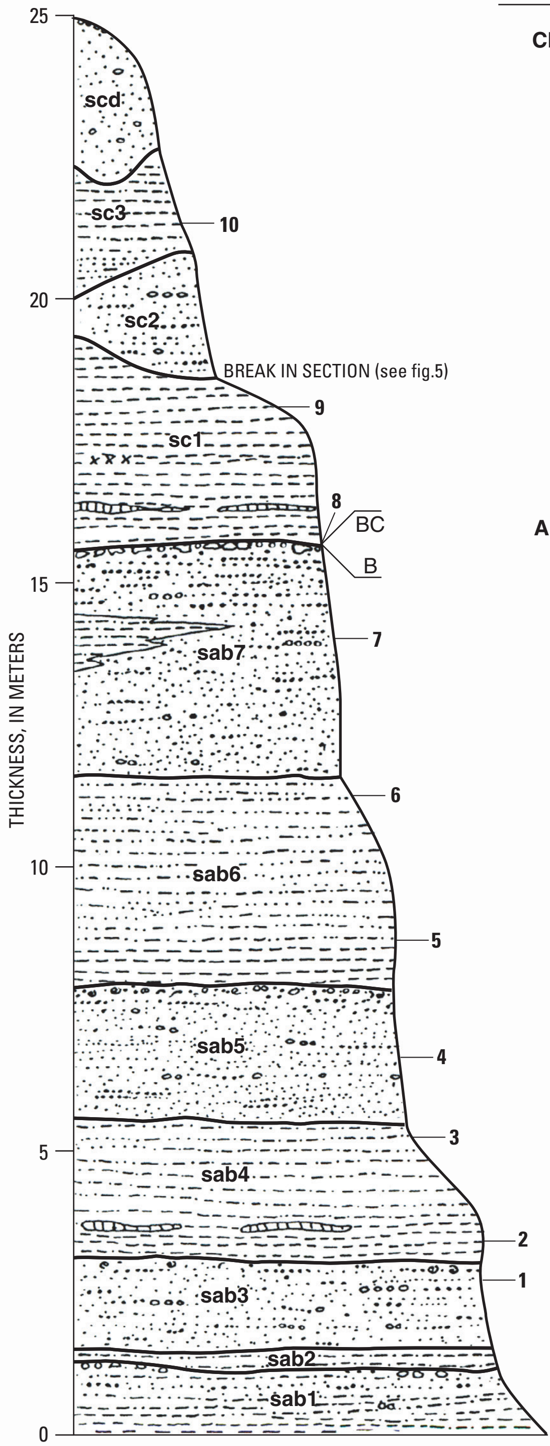
Criteria for Correlating Outcropping Units

Many outcrops of lacustrine sediments look similar to each other. The sizes of clastic fragments deposited at any one site primarily reflect the intensity of the wind-driven bottom currents in that part of the lake. Fragments that were too large (or heavy) for a given current strength were not transported into that area, and fragments that were too small (or light) continued being transported to other areas characterized by lower current strengths. Inasmuch as all ancient lakes of significant size and depth in this basin had areas somewhere on their floors that were characterized by any given bottom-current strength, it is not surprising that lacustrine clastic sediments deposited during one lake cycle are similar to clastic sediments deposited during other lake cycles.

In Searles Valley, however, there is evidence that the maximum wind energy during the times of most intense erosion of shorelines, and rapid transport of material to gravel bars, changed with time. Where lacustrine gravels representing two or more map units coexist, the older unit contains larger fragments than the younger unit. This applies to any combination of units A, B, C, and D. Study of erosional shorelines leads to the same conclusion. Along shorelines carved on older alluvial gravel, where available wave energy removed all fragments smaller than a certain size, the observed minimum sizes of the remaining fragments decrease progressively with decreasing age. For example, in the same part of the basin, erosional shorelines correlative with unit A may include no clasts smaller than 30 cm, those correlative with unit B will have no clasts smaller than 15 cm, and those correlative with unit C will have no clasts smaller than 5 cm. This progression allows the ages of lacustrine gravels and shorelines that cannot be traced directly into a recognizable stratigraphic sequence to be tentatively correlated with one unit.

The most reliable criteria for correlating sediments between separate areas are related to lake-water chemistry, which generally is a basinwide characteristic. Studies of circulation and mixing rates of dissimilar waters in lakes show them to be generally sufficiently rapid for a lake, or each layer in a stratified lake, to approach compositional homogeneity more rapidly than evaporation or other processes can produce compositional diversity (Hutchinson, 1957, p. 282-289, 297; Friedman and others, 1976, p. 506). In lakes the size of Searles Lake, when they are full, one to three weeks would have been adequate for a water mass to traverse the entire periphery of the main body of the lake, a distance of 100 to 150 km. Hutchinson (1957, p. 227, table 21), using one of many available models, calculates current velocities in an unstratified lake by assuming a 100-m-deep lake and wind velocities of 30 and 75 km/hr. Respective current velocities at the surface would be about 15 and 32 km/day, and at the bottom 5 and 12 km/day. The slowest of these would require only 20 days to travel 100 km within a lake, mixing with other lake waters along the entire route.

Figure 6. Stratigraphic column for the type section of the Searles Lake Formation (location: south side of Poison Canyon Amphitheater, pl. 1, sec. H24-f; see also pl. 3*A*), showing units and subunits and their lithologies. Numbers refer to fossil-collection horizons (table 7).



Unit and subunit	Description
CD **scd**	Pebbly sand, tan, top surface covered by scattered lag gravel and an incipient soil; fair to poor sorting, beds locally well developed; basal contact sharp
	UNCONFORMITY—caused by subaerial erosion
C **sc3**	Silt, mostly laminated or thinly bedded with as much as 1 m of very fine sand at base; basal contact sharp
sc2	Sand, fine to coarse, tan or pinkish-tan; locally contains orange-stained pebbles reworked from subunit sab7, fragments of nodose tufa and older lacustrine clay; a few molluscs; basal contact gradational
sc1	Clay and silt, mostly laminated, weather to buff-colored surfaces; 1 m above base is a 3-cm-thick pinkish-tan layer of nodose tufa; about 2 m above the base is a discontinuous thin layer of orange-weathering tuff(?); gypsum crystals locally common; basal contact sharp
	DISCONFORMITY—caused by sublacustrine erosion
AB **sab7**	Sand, generally coarse to very coarse, mostly poorly sorted, especially in upper part, contains pebbles 2–3 cm in diameter, locally includes 1-m bed of calcareous silt near middle of unit; in this area, sand is tan to slightly orange, but in area just west and south, unit is conspicuously orange and its uppermost zone is characterized by conspicuous lag gravel; basal contact gradational
sab6	Silty sand and sand, lower 0.5–1 m is fine grained more calcareous, and lighter colored; unit characterized by discontinuous beds 5–50 cm thick; tan to very pale orange, weathers with puffy surface; in this area has sink holes as much as 3 m deep; a small number of snails and clams noted; contact with underlying unit generally sharp
sab5	Sand, fine in lower part and coarse in upper part; pebbles 2–3 cm across locally common, including fragments of nodose tufa; bedding locally deltaic; molluscs scattered throughout, abundant at top; basal contact gradational in most places
sab4	Silt and very fine sand , calcareous, basal 0.5 m is white laminated marl grading up into light-tan, less well bedded silt and very fine sand; about 1 m up from base is a thin layer of white nodose tufa; gypsum crystals locally abundant; basal contact generally sharp
sab3	Sand, medium to very coarse, local layers of pebbles 2–3 cm in diameter and clay fragments as large as 10 cm; generally horizontally bedded but locally cross bedded, especially in lower half; tan orange to orange; notable concentrations of molluscs in upper 0–2 m; basal contact gradational
sab2	Silt to very fine sand, some clay; faintly bedded; weathers to light tan-green puffy surface, contains a few molluscs; basal contact sharp, locally thins to a single white layer
sab1	Silt and sand; lower half silt and very fine sand, calcareous, faintly bedded, weathers to light-tan puffy surfaces; upper half medium to very coarse sand containing pebbles 2–3 cm in diameter, cross bedded, with a 2-cm orange-stained zone at the top; in places, top of unit represented by a conspicuous lag gravel composed of dark angular fragments of hypabyssal rocks; base not exposed

In Searles Lake, two aspects of lake-water chemistry became expressed in the sedimentary record. The first of these is that the lake water was notably alkaline most of the time, an inference based on the composition of the salt layers and their interstitial brines (Smith, 1979, tables 4, 9, 14, and 16). When voluminous inflow brought large amounts of Ca into the basin, all deposited sediments contained notable concentrations of calcite or aragonite. When inflow was reduced, allowing the salinity to increase, the calcareous sediments had pore waters containing higher percentages of Na, SO_4, or Cl; those sediments now contain trace to moderate amounts of gypsum, thenardite, or halite. Gypsum may have extracted some of its Ca from the enclosing sediments; thenardite and halite probably crystallized after burial from the trapped interstitial brine.

The second indicator of lake-water chemistry stems from the creation of a stratified lake, which happens when a body of saline, relatively dense lake water becomes covered with a layer of fresh, less dense water resulting from seasonal precipitation, melting of glacial ice, or longer term climatic changes (Smith, 1966b, p. 173-174). This structure requires that a seasonal or climatic succession first produced a lake-contraction stage that concentrated the dissolved solids to form a relatively dense water body; this stage then had to be followed by lake expansion caused by an increased fresh-water inflow volume sufficient to create the stratified lake's upper layer. Although some carbonate crystallization also occurred as a result of evaporation, most crystallization probably resulted where mixing took place along the plane between the two parts of the stratified water body. This process, however, would soon deplete those waters of the crystallized components unless circulation were maintained in both layers. While circulation velocities and mixing rates in the lower layers of stratified lakes are difficult to determine, studies show that such circulation does occur. Several models and calculations (Hutchinson, 1957, p. 282-285) conclude that winds produce a sloping of the plane separating two stratified layers and that the "bottom" currents of the upper layer produce drag on the "surface" of the lower layer, causing circulation throughout the lower water body as well.

Stratification of this type is likely to be a basinwide phenomenon, and it provides a mechanism to account for several types of observed evidence that are otherwise difficult to explain. First, the mineralogy of the subsurface saline layers indicates that the dissolved components of the enlarged lakes included substantial percentages of Na and CO_3 (Smith, 1979, p. 84-96), so a lake-water pH of at least 9 is likely for all except the most dilute stages. When more Ca was introduced with each annual influx of fresh water, most of it should have precipitated as aragonite or calcite near the inlet, where the fresh water first mixed with the high-pH water, to make a "chemical delta." Some stratigraphic units, however, have a high $CaCO_3$ content over most of the basin, raising questions as to how the Ca avoided precipitation at the inlet. Postulating a stratified lake, with a layer of fresh, Ca-bearing water

Figure 7. Outcropping subunits sb1 through sb4 and unit BC (sbc) of the Searles Lake Formation. Unit BC here consists of windblown sand; the subunits below it are lacustrine deposits. View toward north; location: plate 1, sec. H14-r.

that could spread throughout the basin, solves this problem. Later, the Ca in the surface layer precipitated when that layer warmed, evaporated, or mixed with the underlying layer along the chemocline. Postulating a stratified layer also explains the apparent cycles of carbonate deposition, expressed as alternating layers of white and greenish laminae in both subsurface and outcrop samples (fig. 10). Smith (1979, p. 79-80) calculates the amount of annual $CaCO_3$ deposition required to produce the amounts reported by analyses of subsurface laminated sediments and finds the amounts plausible. These laminae could have been caused by the seasonal nature of either the snowpack melting in early summer or the evaporative removal of the surface-water layer during summer and autumn. The fresh upper layer of a stratified lake would provide protection over much of its floor from strong wind-driven currents that the preservation of fine—sometimes paper-thin—laminae requires, and a saline lower layer would tend to exclude burrowing organisms that would also disrupt the laminae.

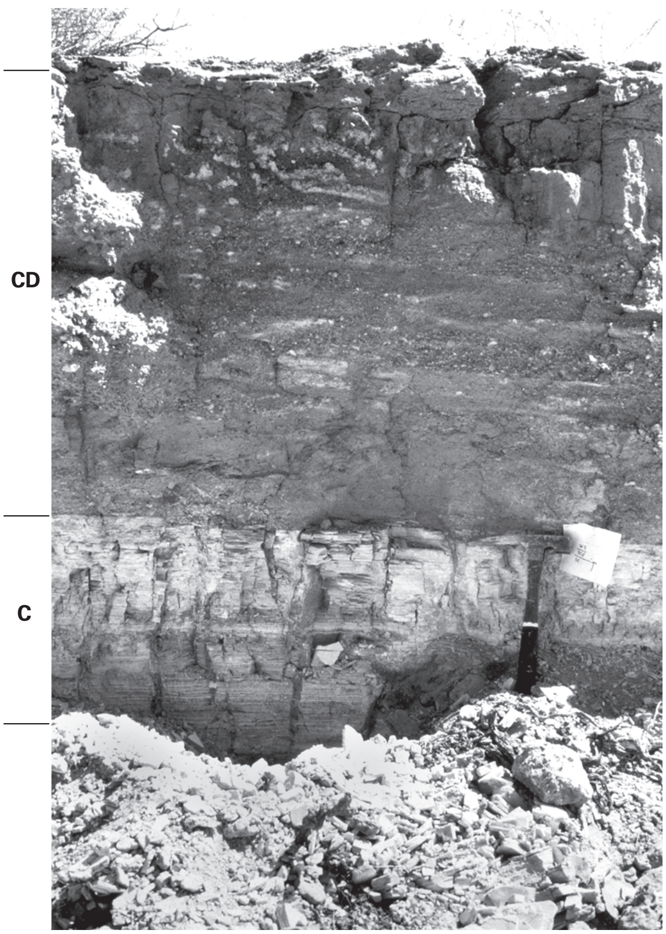


Figure 8. Exposure of Searles Lake Formation unit CD (about 75 cm thick, with moderately developed calcareous soil on top), here underlain by unit C (about 40 cm of laminated lacustrine sediment) and overlain by 10 cm of windblown sand and colluvium. Location: plate 1, sec. I30-c.

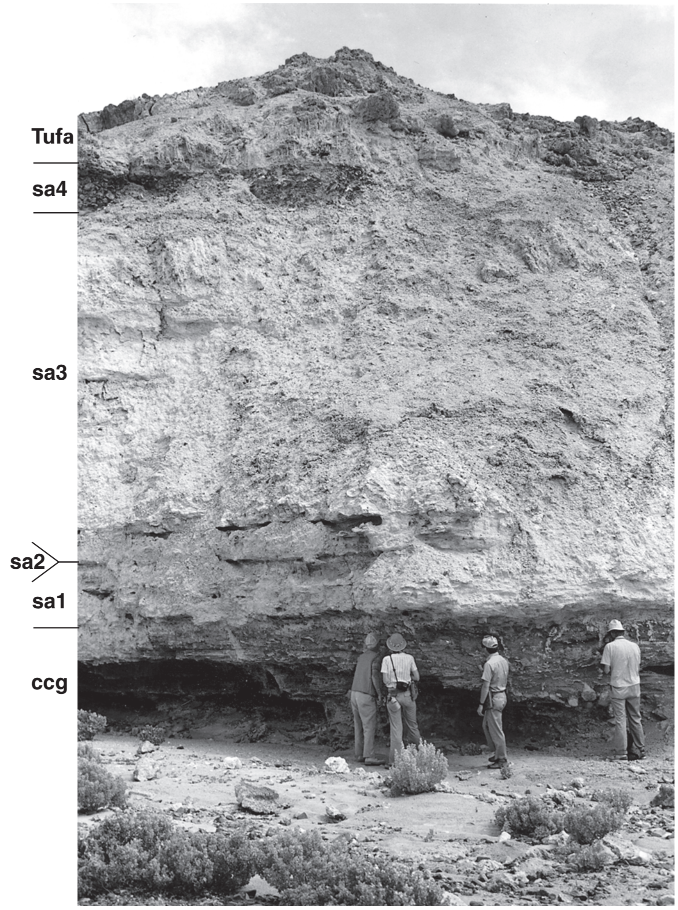


Figure 9. Exposure of subunits sa1, sa3, and sa4 of Searles Lake Formation totaling 8.6 m in thickness, resting on Christmas Canyon Formation unit (ccg), and overlain by tufa (see appendix 1, reference section I32-r). Subunit sa2, as much as 0.5 m thick elsewhere in this wash, is here represented only by a very thin layer. Tufa above subunit sa4 (dark gravel) ^{14}C dated as 13,700±50 yr B.P.; two ^{14}C dates on marl immediately under sa4 gravel and 50 m to left of photograph area, which are considered erroneous, are 21,910±100 yr and 21,330±80 yr.

Stratification was not, however, an ever-present feature of the lake structure. Many outcrop units are unlaminated, and other units, in areas away from the inlet, are characteristically less calcareous, a property that is expressed by darker outcrop colors and orange or tan hues. The evidence for or against stratification, therefore, becomes a basinwide criterion that helps identify the unit to which isolated outcrops should be assigned. Where sequences of units are present, sequences of paleolimnological reconstructions help test alternative correlations.

Another criterion used to identify units in the field is the type and abundance of tufa found as fragments, interbedded layers, or buried where attached to a substrate. As noted in the section on tufa of the Searles Lake Formation, Scholl (1960, p. 416-421) divided the tufa types in Searles Valley into seven groups, which have been combined in this report into two types, the relatively dense and structureless "lithoid" variety and the nodular or lobate "nodose" variety. The period of most intense growth of nodose tufa was at the end of deposition of unit B, and unit BC in many areas is identifiable because it is a lag gravel composed almost entirely of fragmented nodose tufa (fig. 11). Apparently, large quantities of this recently formed tufa were eroded and spread by strong currents over much of the south third of Searles Valley, making this horizon into a time line.

Fossil soils, along with stratigraphy, are used to identify certain alluvial units. These soils were developed on four units in the Searles Lake Formation—on an alluvial layer within unit A and on the tops of units AB, BC, and CD. The soil within unit A characteristically has a densely reticulated calcite zone as much as 1 m thick and a 10- to 20-cm-thick zone of gray-orange coloration at its top (fig. 12*A*); except for the grey-orange zone, it is similar to the soil developed on the Christmas Canyon Formation and older gravel. Although not always a "soil" in the pedogenic-profile sense, a zone believed to represent a fossil desert varnish on the top of unit AB indicates a period of subaerial exposure as does a soil; the original iron oxide component of the desert varnish has now mostly hydrated to produce limonite or geothite, minerals with distinctive orange to brown colors that now characterize this horizon. However, pedogenic calcareous concentrations are locally found in this zone (fig. 12*B*), thus supporting its designation throughout the region as a fossil soil. The soils on units BC and CD characteristically consist of a zone of dispersed calcareous pods, 1-2 cm in diameter, and both the pods and matrix material are infiltrated by a network of hairline, pale red (10R5-6/2-4) marks of indeterminate origin. The soil on unit BC, however, is more extensively developed, contains a small amount of clay, and generally extends downward about

Figure 10. Laminated sediments of subunit sc1 of Searles Lake Formation (knife is 9 cm long). Thin white layers are aragonite laminae, interbedded with dark gray silt and clay (top and bottom). Location: plate 1, sec. I23-r.

Figure 11. Outcrop showing horizontal contact between units B and C of the Searles Lake Formation. Units B and C together are here about 3 m thick. Unit BC is represented by a thin lag gravel bed (arrow) composed of white nodose tufa fragments. Many tufa masses, which were formed near the close of unit B deposition, were fragmented and spread by waves of the retreating lake responsible for unit B or the advancing lake responsible for unit C. View to south; location: plate 1, sec. L5-j.

30 cm (fig. 13*A*), whereas the soil on unit CD contains virtually no clay and most commonly extends downward about 20 cm (fig. 13*B*).

The lithologic characteristics used in the field to identify the major units of this formation are summarized in table 4. During mapping, outcrops that were small or isolated from areas having convincing stratigraphic sequences were assigned to units on the basis of these criteria. A few sedimentary units with apparently reliable ^{14}C dates were assigned to the appropriate map unit on that basis, providing the lithologic and stratigraphic evidence did not contradict that assignment. As discussed later, ^{14}C ages on these sediments were used cautiously. Only where two or more dates on different materials from the same unit were substantially the same, and where lithologic and stratigraphic criteria were not diagnostic, were stratigraphic assignments based on dates.

Criteria for Correlating Outcropping Units with Subsurface Units

Correlations between outcrop and subsurface deposits are based on four types of physical evidence, supplemented by radiometric ages. The physical evidence:

(1) When tracing outcropping units toward Searles Lake, each unit reaches a point where it becomes covered by younger deposits, which themselves eventually disappear beneath the dry-lake surface. The succession of outcrop units can then be correlated with the succession of subsurface units. For example, along the northeast, south, and southwest edges of the now-dry lake, the sediments of units C and CD can be traced to the edges of the lake and can be seen disappearing under sediments of unit D which, in the valley center, is the Overburden Mud in subsurface stratigraphic terms (table 3). Around the flanks of the basin, all units older than unit C are observed being covered by successively younger units when traveling lakeward.

(2) The lithologies of the outcrop units help verify these correlations by being geologically reasonable equivalents of the subsurface deposits. For example, alluvial gravels must be the upslope lateral equivalents of shallow- or dry-lake stages. Similarly, greenish-hued, high carbonate or laminated lake deposits found at high levels around Searles Valley are reasonably correlated with mud layers having similar characteristics in subsurface records, as both indicate perennial-lake depositional environments.

(3) The apparent stability in the levels of lakes responsible for a succession of sediments also provides a basis for their correlation. For example, outcrops of thick perennial-lake deposits are reasonable correlatives of thick subsurface

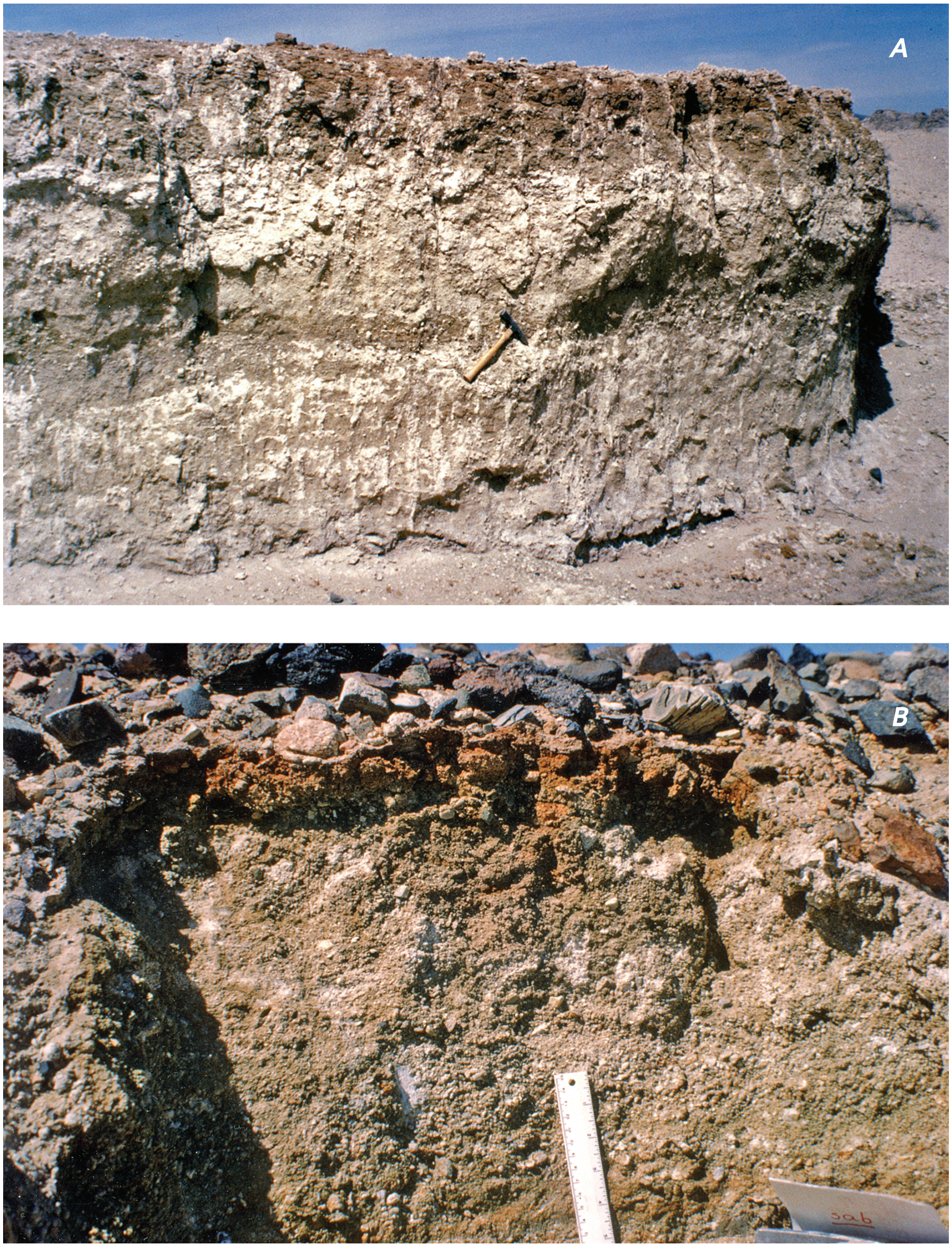


Figure 12. Older fossil soils of the Searles Valley area. *A*, Exposure of two fossil soils. Lower calcareous soil (below sharp end of pick) is on Christmas Canyon Formation; it is about 1 m thick and characterized by white pods (plus horizontal and vertical stringers) of calcite-rich material and a gray-green matrix. Upper calcareous soil (below top of exposure) is on alluvial unit sa2 of the Searles Lake Formation; it is similar in thickness, mineralogy, and structure to lower soil, except that the matrix of top 50 cm is reddish brown, a characteristic of this soil. Pick handle is 28 cm long. *B*, Detailed view of fossil soil on top of unit AB of Searles Lake Formation. This soil is very commonly characterized by a strong orange or orange-brown zone (here, 5 cm thick) at the top, less commonly also by white calcareous pods as seen here. Ruler is 12 cm long.

Figure 13. Younger fossil soils of the Searles Valley area. *A*, Fossil BC soil showing white calcareous pods with pink coloration on them as well as on pebbles and matrix. Soil here is about 40 cm thick; top is at undissected surface, 5 cm above upper end of 30-cm-long ruler. Some pedogenic clay is present in upper 30 cm of the soil. *B*, Fossil CD soil showing small calcareous pods in lower part of preserved soil profile, which is here about 20 cm deep (ruler is 15 cm long). Several characteristics of CD soil are similar to those of the BC soil, except that the younger CD soil is thinner, the calcareous pods are smaller, the pink coloration is less intense, and pedogenic clay is present only in very small amounts.

units composed of marl or fine clastics, as both indicate long periods of deposition in a deep lake. Outcrops of alternating, relatively thin, fine- and coarse-clastic subunits are reasonable correlatives of subsurface sequences made up of alternating thin layers of marl and salt, as both indicate a fluctuating lake history.

(4) As noted earlier, the abundance of carbonate in deposits far from the inlet and the presence or absence of laminae in these deposits are interpreted to be evidence of the presence or absence of stratification in the lake. Because outcrop units B and C both display laminae, the deposits of units B, BC, and C are correlated with the subsurface Parting Mud, the upper part of which is prominently laminated (Smith and Haines, 1964, fig. 14). Deposits of subunits sc1 and sc3 of unit C are consistently characterized by fine, light-colored or white (aragonite) laminae, whereas deposits of unit B and its subunits may be finely or coarsely laminated or unlaminated, and the laminae may be white, gray, light orange, or various shades of green. Fine laminae couplets in outcrops are typically 1 to 5 mm thick (fig. 10), and coarse laminae couplets may be as thick as 10 to 40 mm. Further corroboration of the proposal that the presence, absence, and character of laminae represents a reliable basis for making correlations between exposures and subsurface deposits is presented later in the section on Paleolimnology, Low-Energy Environments, where their use in reconstructing changes in lake levels is also explored.

Criteria for Identifying Disconformities

As a result of the numerous oscillations in lake level during the period that the Searles Lake Formation was being deposited, both alluvial and lacustrine deposition was interrupted many times, each time introducing the potential for a disconformity accompanied by a loss of section. A disconformity is clear where one or more units or subunits are found to be missing. Where no units are lost, however, only differences in thickness would document a loss of section, but lacustrine sediments around the edge of a basin vary greatly in thickness over short distances, making that test unreliable. Other evidence, such as angular discordance of superimposed beds or channeling of the underlying sediment, is locally observed.

In mapping units and subunits of the Searles Lake Formation, several sequences composed solely of lacustrine sediments, which initially appeared to represent "layer cake" stratigraphy, were eventually found to include major hiatuses that were overlooked at first because they were not accompanied by any geological criteria of erosion. These were suspected of being the result of sublacustrine erosion. The mechanism inferred for this process is as follows (fig. 14): During the retreating stage of the lake, when the deep-water sedimentation ceased, nearshore processes began depositing a sandy layer that covered the deeper water sediments. As the lake continued to retreat, wind-driven currents reworked these unconsolidated shallow-water sediments, producing structures characteristic of that environment. At any given time, the

Table 4. Generalized field characteristics of major units of Searles Lake Formation, primarily in the Poison Canyon area (pl. 3*A*) and The Pinnacles area (pl. 4).

Unit	Fine facies		Coarse facies	Tufa type and form
	Lithologic character	Color range (outcrop dry)		
D	Silt, massive, "puffy" surface on outcrop, cemented by halite in fresh exposures, white efflorescence, lacustrine	Light brown (5YR6/4) to grayish orange (10YR7/4)	Angular pebbles, grayish orange mixed with silt, lacustrine and alluvial	None
CD	Pebbly sand, soft, alluvial	Dusky yellow (5Y6/1) to grayish orange pink (5YR7/4)	Pebble, cobble, to small-boulder gravel, fine- to medium- sand matrix, massive, soft, alluvial, fossil soil on top 20 cm thick	None
C	Silt, very calcareous and gypsiferous, thinly laminated, well indurated, lacustrine	Dusky yellow (5Y6/2) to moderate greenish yellow (10Y7/2)	Pebble gravel, rounded to subrounded, lacustrine, moderate varnish	Nodose tufa, as growths and fragments, tufa layer near base
BC	Sand, subangular, fairly well sorted and cemented, cross-bedded, lacustrine	Grayish orange pink (5YR7/2) to grayish orange (10YR7/4)	Angular alluvial rubble near bedrock outcrops, gray to dark brown, fossil soil 30 cm thick with calcareous pods 1-2 cm in diameter	Abundant fragments of nodose tufa
B	Silt to sand, moderately well sorted, less calcareous than unit C, coarsely laminated or unlaminated, high percentage of greenish mica, lacustrine	Light olive gray (5Y5/1) to moderate greenish yellow (10Y7/2)	Pebble to cobble lacustrine gravel, very calcareous, rounded, heavy varnish	Abundant growths of nodose tufa, medium to dark brown
AB	Alternating silt and sand, silt locally calcareous near base, sand commonly cross-bedded	Pale brown (5YR5/4) to grayish orange (10YR7/6), distinctly orange at top of unit	Angular alluvial rubble near bedrock outcrops, very dark brown varnish with orange hues, fossil "soil" most commonly an orange zone 5-30 cm thick (weathered desert varnish?), locally contains pedogenic calcite	Rare, thin layers, both lithoid and nodose types
A	Silt to coarse sand, silt is very calcareous, coarse sand well cemented by calcite, indistinct bedding	Moderate yellow (5Y7/1) to pale greenish yellow (10Y8/2)	Cobble to boulder gravel, lacustrine, angular to slightly rounded, heavy varnish; fragments in alluvial bed(s) angular to slightly rounded; calcareous soil, about 1 m thick, present within unit, with orange zone at its top	Lithoid tufa, massive deposits, forms bulk of The Pinnacles and tufa concentrations near highest shoreline, grayish orange

strength of bottom currents was fairly uniform over areas that lie at about the same depth, and this produced a shallow-water erosion-and-redeposition surface that was notably planar. If the lake retreated below the level of the outcrop being observed, subaerial erosion processes began to alter this planar surface. Later, when the lake again expanded and its waters readvanced, a second episode of shallow-water erosion-and-deposition took place, reworking the upper part of the soft, subaerially eroded older beach sediment, usually obliterating any small channels on its upper surface that had developed subaerially. As the lake deepened and lake-floor currents diminished, shallow-water sand began to accumulate on this planar surface. Later, deep-water sedimentation returned.

The most distinguishing characteristics of sublacustrine erosion are planar horizons at the base of the sediments representing the return of lacustrine deposition and an absence of subaerial channel structures. These planar surfaces may be conformable or uncomformable relative to the dips of beds deposited during the previous cycle. In either case, the uncomformity represents the zone of interrupted deposition and possibly missing sediments. If it is comformable, the uncomformity generally lies within the coarse-grained units composed of shallow-water sand or gravel rather than at the boundaries between fine- and coarse-grained lithologies (fig. 15). Many of the sand units in the Searles Lake Formation display a change in bedding, color, or fragment size near the middle of the bed, and this probably represents the actual hiatus (fig. 15). Where the planar sublacustrine erosion surface is disconformable, the sand that represented the retreating lake is lost.

Good examples of sublacustrine unconformities are found in the Poison Canyon area (pl. 3*A*). One is found where unit C rests disconformably on subunit sab7 of unit AB at the type section for the Searles Lake Formation (fig. 6), on the south side of the amphitheater. Two more unconformities are found on the north side of the amphitheater—one is where subunits sb1, sb2, sb3, and sb4 of unit B are truncated by a planar surface that was created by the readvance that led to the deposition of unit C (sec. H14-r); the other is where subunits sab4, sab5, sab6, and sab7 of unit AB are missing because they were truncated by the readvancing lake that deposited subunit sb5 of unit B (sec. H23-c, f). In a broad area between the east end of the Spangler Hills and the railroad tracks (pls. 3*A* and 4), deposits of unit D rest directly on an originally near-planar surface cut on units B and C. On the east edge of Teagle Wash (sec. L8-k), erosion has exposed a vertical cross section clearly showing the unconformable relations and the planar surface cut by this sublacustrine-erosion process (fig. 16, pl. 4).

Radiometric Ages of Exposed Units

The estimated ages of stratigraphic units in the Searles Lake Formation are primarily based on correlations between each unit or subunit and the equivalent subsurface deposit, which includes the Bottom Mud and all overlying units. These subsurface deposits are the sources of 30 U-series dates on salts and more than 50 finite ^{14}C dates (that is, not open-ended minimum ages) on lacustrine organic carbon that I consider to be less susceptible to large errors than are radiometric dates on inorganic carbonates and many other outcrop materials. The stratigraphy of the subsurface deposits is also more straightforward than that of the outcropping sediments. Confidence in the subsurface age control also stems from the observations that subsurface dates on organic carbon from one core closely resemble dates from carbon in the same unit or horizon in another core obtained several kilometers away and that the ages become younger moving stratigraphically up through the section and rarely show reversals of more than a few hundred years.

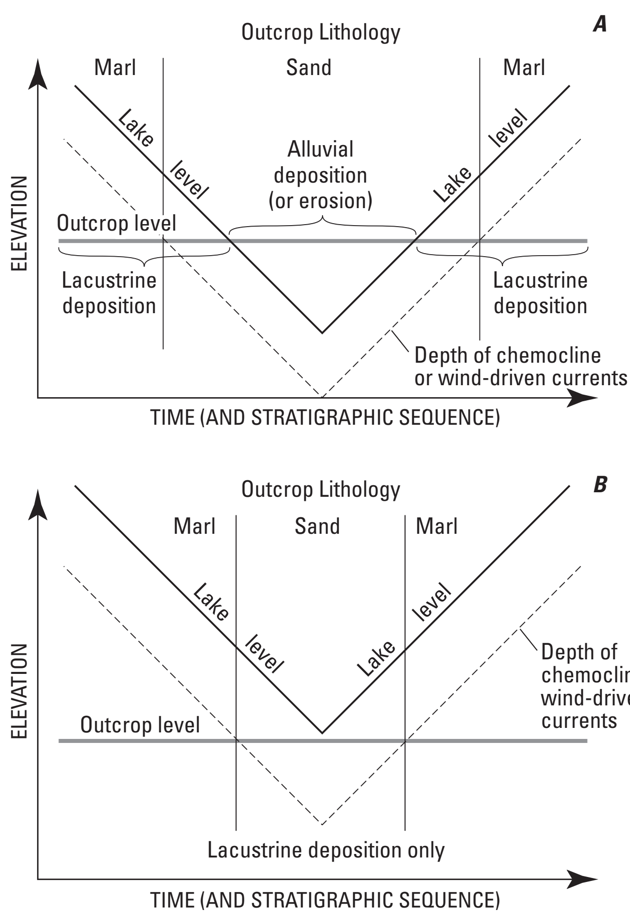


Figure 14 Diagrams showing inferred depositional history recorded by a marl-sand-marl sequence of outcropping deposits from a lake of varying level. Time and stratigraphic sequence progress toward the right. Both A and B start and end with deposition of marl in water lacking bottom currents strong enough to transport sand. This condition could result from (1) the water depth being or becoming great enough to reduce wind-driven bottom currents to negligible velocities or (2) the chemocline in a stratified lake being or rising above the outcrop elevation, effectively insulating the bottom sediments from the effect of winds. A lithologic contact resulting from a rising chemocline would be a sharp one; a contact resulting from depth change in an unstratified lake would be a gradational one, because bottom currents would vary in strength as storms came and went. A, The inferred sequence as the lake level falls, eventually below the elevation of the outcrop, and then again rises to become a deep, possibly stratified, lake. This makes the resulting sand bed a potential record of three successive events: (1) lacustrine sand deposition in the shallow water around the edge of a falling lake, (2) subaerial alluvial deposition or subaerial erosion, and (3) lacustrine sand deposition in the shallow water around the edge of a rising lake. If the alluvial deposits or subaerial erosion channels of step 2 were removed by sublacustrine erosion as the lake reexpanded, the sand layer would only record lacustrine deposition, with a hiatus in deposition occurring somewhere near its middle. B, Sequence as in A, except that lake level does not fall below outcrop level, so the resulting deposit is entirely lacustrine. The low point of the lake-level oscillation would, however, again be near the middle of the sand layer.

Figure 15. Lacustrine sand facies of unit BC of the Searles Lake Formation (dark, partly cross-bedded interval), here exposed between lighter colored, finer sediments of subunits sb6 (below) and sc1 (above). Lower half or two-thirds of sand bed is attributed to sedimentation during the retreat of lake that deposited unit B, and upper part of sand bed is attributed to sedimentation as lake was readvancing, eventually to deposit sediments of unit C (see fig. 14). Alluvial deposits mapped as part of unit BC are present 40 ft (12 m) below the elevation of this outcrop, so a break in lacustrine deposition had to occur at this level. This break is inferred to be either at top of uniform zone of foreset beds making up lower half of sand unit, or at the higher horizon (aligned with 18-cm white scale) where horizontal bedding begins. Searles (dry) Lake is to the left; location: plate 1, sec. I19-f.

The base of the oldest outcrop unit included in the Searles Lake Formation is correlated with the base of the Bottom Mud, which is now considered to have an age of about 150 ka. The earlier age estimate of about 130 ka for this contact (Stuiver and Smith, 1979, p. 75) has been revised in view of two studies of Searles Lake cores, the U-series dating by Bischoff and others (1985, fig. 2) and the combined radiometric-date and sedimentation-rate estimates by Jannik (1989, figs. 25, 26). This revised age is about 10 k.y. older than the midpoint age of a major climatic change indicated by a U/Th-dated isotopic study of calcite veins in an area about 50 km east of Death Valley (Winograd and others, 1988, fig. 4; Winograd and others, 1992, p. 257, fig. 4) and the Vostok ice core from Antarctica (as interpreted by Winograd and others, 1992, p. 257, fig. 4, and footnote 14).

Radiocarbon dates were determined on various types of material from outcrops in Searles Valley (table 5; fig. 17). The samples were collected from below the weathered zone and carefully checked with a hand lens for secondary carbonate. Samples of marl were collected from zones far enough in from the outcrop face to be free of any weathering cracks, veins, or other signs of penetration by postdepositional waters. In the laboratory, all 36 tufa samples, 10 of which were examined in thin section and confirmed to be free of recrystallized carbonate, were crushed until the fragments were 3 to 5 mm in diameter. Most were also studied using X-ray diffraction; contaminated tufa samples composed of aragonite can be identified by the presence of detectable percentages of calcite, which is almost always the secondary carbonate. These, as well as samples containing oolites, mollusks, or ostracodes, were soaked and disaggregated in water (using an ultrasonic bath if needed), placed in screens finer than the material being purified, and washed with a high-velocity water spray until all attached sediment was removed. After drying at room temperature, the sample material was hand picked until believed to be pure. Organic carbon was recovered by digesting the carbonaceous marl or tufa in HCl until no carbonate remained. All carbonate samples, except marl, were partially dissolved in acid before the carbonate used for analysis was extracted. Neither wood nor charcoal suitable for ^{14}C dating was found in outcrops.

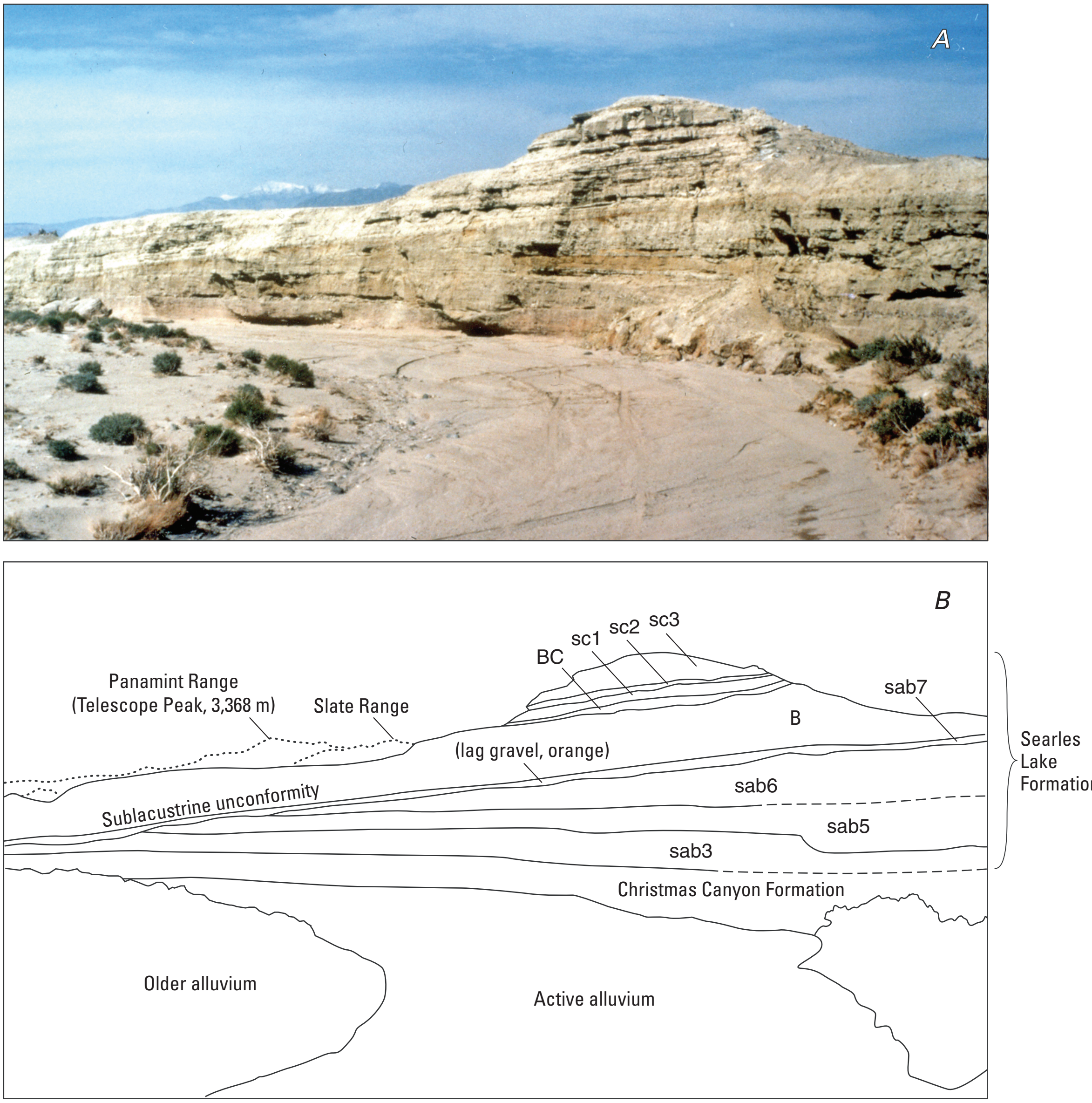


Figure 16. Photograph and diagram of outcrop showing sublacustrine angular uncomformity within Searles Lake Formation. (Note: In the early 1980's, this outcrop was severely eroded by flood waters that moved the face of the lacustrine deposits away from the camera position as much as 3 m, so that present outcrop appears different.) *A*, View of outcrop looking northeast; unconformity is along top of beds having orange hues. Note planar form of unconformity surface and lack of channels; outcrop about 10 m high. Location: plate 1, sec. L8-k. *B*, Identification of units exposed in outcrop photograph; see measured section L8-k in appendix 1 for lithologies.

Table 5. Radiometric ages of deposits assigned to the Searles Lake Formation.

[Listed in descending stratigraphic order of unit, within unit by decreasing elevation. Precision of locations indicated by significant figures in latitude and longitude estimated when sample was obtained.]

Unit	Map location code	Latitude	Longitude	Elevation (ft)	Sample material[1]	Age[2] (yr)	± (yr)	Laboratory no.[3]
CD	I18-a	35°40.62′	117°23.06′	1,690	S	(16,200)	300	Y
C	K22-e	35°34.68′	117°27.34′	2,260	L	17,000	1,000	B90-5 (U) [6]
	K22-e	35°34.68′	117°27.34′	2,260[4]	L	10,900	40	USGS-2845[6]
	M18-g	35°35.2′	117°16.9′	2,050	N	12,000	400	W-1317
	H28-d	35°39.4′	117°28.3′	2,030	O	11,730	350	W-1327
	L12-n	35°35.8′	117°18.4′	1,960	N	12,110	300	W-1325
	H28-f	35°39.2′	117°28.0′	1,940	N	12,700	60	USGS-2328A
	H28-f	35°39.2′	117°28.0′	1,940[4]	N	12,910	50	USGS-2328B
	L18-n	35°34.8′	117°24.0′	1,935	N	12,200	450	W-1318
	L18-n	35°34.8′	117°24.0′	1,935[4]	C[5]	11,720	500	W-1418
	C14-f	35°50.8′	117°18.4′	1,920	N	14,300	200	USGS-33A
	C14-f	35°50.8′	117°18.4′	1,920[4]	N	12,800	150	USGS-33B
	H23-l	35°39.92′	117°25.90′	1,875	S	11,700	160	Y
	L7-p	35°35.67′	117°23.75′	1,870	O	11,020	400	W-1679
	L7-p	35°36.67′	117°23.75′	1,870[4]	O	11,820	400	W-1680
	H23-j	35°39.84′	117°25.29′	1,855	S	14,210	200	Y
	C15-r	35°50.4′	117°18.8′	1,850	N	13,830	500	W-1893
	C15-r	35°50.4′	117°18.8′	1,850[4]	N	13,650	500	W-1890
	H23-j	35°39.89′	117°25.27′	1,845	N	10,430	100	Y
	H23-f	35°39.96′	117°25.85′	1,840	C[5]	13,750	160	Y
	H23-j	35°39.93′	117°25.25′	1,840	N	14,140	120	Y
	H24-b	35°40.32′	117°24.46′	1,760	N	13,300	500	W-1201
	I32-r	35°37.4′	117°22.0′	1,750	N	13,700	350	W-1323
	I18-a	35°40.63′	117°23.06′	1,680	C[5]	13,200	200	Y
	I18-a	35°40.63′	117°23.08′	1,670	C[5]	13,350	200	Y
B	C3-a	35°52.7′	117°18.8′	2,110	Q	(9,070)	300	W-1894
	C3-a	35°52.7′	117°18.8′	2,110[4]	M	(7,700)	75	USGS-67
	M18-k	35°35.0′	117°16.9′	2,040	M	13,635	45	USGS-2521
	M18-c	35°35.3′	117°17.1′	2,030	L	21,160	+1,325 -1,075	B86-38 (U)
	M18-c	35°35.3′	117°17.1′	2,030[4]	L	21,000	+2,543 -2,419	B-86-37 (Pr)
	M18-g	35°35.1′	117°16.8′	2,020	N	13,520	120	USGS-2320
	H28-f	35°39.10′	117°28.03′	1,910	M	15,020	80	USGS-2424
	H28-g	35°39.1′	117°27.9′	1,910	M	15,220	100	USGS-2523

Table 5. Radiometric ages of deposits assigned to the Searles Lake Formation.—Continued

[Listed in descending stratigraphic order of unit, within unit by decreasing elevation. Precision of locations indicated by significant figures in latitude and longitude estimated when sample was obtained.]

Unit	Map location code	Latitude	Longitude	Elevation (ft)	Sample material[1]	Age[2] (yr)	± (yr)	Laboratory no.[3]
	L8-n	35°35.7′	117°22.8′	1,850	O	14,950	500	W-1904
	C15-q	35°50.4′	117°19.2′	1,850	N	15,250	60	USGS-2527
	H23-j	35°39.9′	117°25.4′	1,850	N	12,965	45	USGS-2526
B	H14-r	35°40.43′	117°25.32′	1,840	M	20,210	90	USGS-2321
	L8-n	35°35.6′	117°22.9′	1,840	C[5]	16,970	400	Y
	H23-f	35°39.99′	117°25.85′	1,830	O	16,820	200	Y
	H23-a	35°40.32′	117°25.48′	1,830	M	21,020	200	USGS-2425
	H14-r	35°40.39′	117°25.35′	1,810	N	22,500	600	W-1324
	I32-r	35°37.4′	117°22.0′	1,780	M	24,090	270	USGS-2525
	H23-b	35°40.28′	117°25.48′	1,780	M	(30,510)	210	USGS-2102
	H23-b	35°40.28′	117°25.48′	1,780[4]	M	(32,960)	420	USGS-2326
	H23-a	35°40.35′	117°25.35′	1,780	M	26,140	140	USGS-2423
	H23-g	35°40.07′	117°25.52′	1,760	S	17,750	140	USGS-2422
	H23-g	35°40.07′	117°25.51′	1,750	S	18,600	130	USGS-2103
	H23-g	35°40.07′	117°25.51′	1,750	M	18,560	210	USGS-2327
	I30-h	35°38.8′	117°23.0′	1,645	M	19,150	600	W-1905
AB	H28-f	35°39.2′	117°27.9′	1,950	M	(26,450)	140	USGS-2522
sab6	H23-c	35°40.25′	117°25.77′	1,820	M	(29,960)	250	USGS-2106
	H23-h	35°39.96′	117°25.29′	1,765	O	(32,100)	1,000	Y
	H24-f	35°40.12′	117°24.85′	1,760	M	25,740	130	USGS-2104
sab4	H24-e	35°40.04′	117°25.14′	1,740	N	28,800	400	Y
	H24-e	35°40.07′	117°25.13′	1,740	O	27,800	1,200	Y
	H24-r	35°39.61′	117°24.29′	1,720	S	27,400	800	W-1922
sab3	H23-f	35°40.13′	117°25.91′	1,830	S	26,650	860	USGS-2105
	H23-c	35°40.15′	117°25.75′	1,790	M	29,130	160	USGS-2426
	H23-b	35°40.22′	117°25.77′	1,780	M	27,880	210	USGS-2322
	H24-f	35°40.11′	117°24.86′	1,735	S	29,200	2,000	W-1575
	H24-e	35°40.09′	117°25.13′	1,735	S	(35,000)	1,600	Y
sab2	C3-r	35°52.2′	117°18.9′	2,070	M	(10,610)	50	USGS-2325
A	N12-m	35°30.78′	117°25.07′	2,200	L	(10,230)	300	W-1322
	K24-g	35°34.7′	117°24.5′	1,930	M	(17,620)	+549 -376	B-84-18a (U)
	L18-g	35°35.3′	117°23.5′	1,870	M	(30,380)	280	USGS-2520
	L5-j	35°36.8′	117°22.2′	1,810	L	(32,500)	2,000	W-1321
	H23-f	35°40.01′	117°25.82′	1,810	S	40,000	2,500	Y
	L5-b	35°37.1′	117°22.4′	1,800	L	> 36,000	--	GX-11935

Table 5. Radiometric ages of deposits assigned to the Searles Lake Formation.—Continued

[Listed in descending stratigraphic order of unit, within unit by decreasing elevation. Precision of locations indicated by significant figures in latitude and longitude estimated when sample was obtained.]

Unit	Map location code	Latitude	Longitude	Elevation (ft)	Sample material[1]	Age[2] (yr)	± (yr)	Laboratory no.[3]
	L5-b	35°37.1′	117°22.4′	1,800[4]	L	(31,700)	+1,074	B-86-3 (U)
A							-800	
	H23-f	35°40.01′	117°25.88′	1,800	L	(32,800)	390	USGS-2324A
	H23-f	35°40.01′	117°25.88′	1,800[4]	L	(33,370)	330	USGS-2324B
	H23-f	35°40.07′	117°25.84′	1,780	M	(30,900)	260	USGS-2323
	I32-r	35°37.3′	117°22.1′	1,750	M	(21,910)	100	USGS-2329A
	I32-r	35°37.3′	117°22.1′	1,750[4]	M	(21,330)	80	USGS-2329B
	I32-r	35°37.4′	117°22.0′	1,730	L	(85,400)	4,000	B90-1 (U)[6]
	I32-r	35°37.4′	117°22.0′	1,730[4]	L	(25,400)	140	USGS-2841[6]
	I32-r	35°37.4′	117°22.0′	1,730	L	(65,600)	3,000	B90-2 (U)[6]
	I32-r	35°37.4′	117°22.0′	1,730[4]	L	(29,100)	240	USGS-2842[6]
	I32-r	35°37.4′	117°22.0′	1,730	L	(164,000)	9,000	B90-3 (U)[6]
	I32-r	35°37.4′	117°22.0′	1,730[4]	L	(32,300)	290	USGS-2843[6]
	I32-r	35°37.4′	117°22.0′	1,730	L	(25,300)	1,000	B-90-4(U)[6]
	I32-r	35°37.4′	117°22.0′	1,730[4]	L	(18,000)	170	USGS-2844[6]

[1]Abbreviations for dated materials: C, organic carbon; L, lithoid tufa; M, marl or calcareous sandstone; N, nodose tufa; O, oolites; Q, ostracodes; S, mollusks.

[2]Ages believed to be unreliable are enclosed by parentheses. They are judged to be unreliable because greatly different from ages believed to be correct for their stratigraphic assignment or greatly different from dates on more reliable material from nearby outcrops of the same unit.

[3]Laboratory prefix codes and managers; ^{14}C method except as noted: W-, M. Rubin, USGS, Washington, D.C., or Reston, Va.; USGS-, S. Robinson and D. Trimble, USGS, Menlo Park, Calif.; B- (U-series disequilibrium or Pr method), J.L. Bischoff, USGS, Menlo Park, Calif.; Y, M. Stuiver, Yale University, New Haven, Conn. (laboratory numbers not assigned); GX-, Kruger Enterprises, Inc., Cambridge, Mass.

[4]Duplicate determination of preceding sample.

[5]Sample W-1418 is organic carbon from nodose tufa; sample materials labeled C and having Y laboratory designations are organic carbon from marl.

[6]Ten samples in this table are paired U-series dates followed by ^{14}C ages on identical samples. See Garcia and others (1993) for details of sample locations. Three pairs are from subunits sa1 and sa3 collected from localities within a few meters of each other; the first two (B-90-1/USGS-2841 and B-90-2/USGS-2842) were believed to come from the same bed only 10 m away. The fourth locality (B-90-4/USGS-2844) is about 160 m south of the first three and may represent unit A or unit B; it is here placed under unit A.

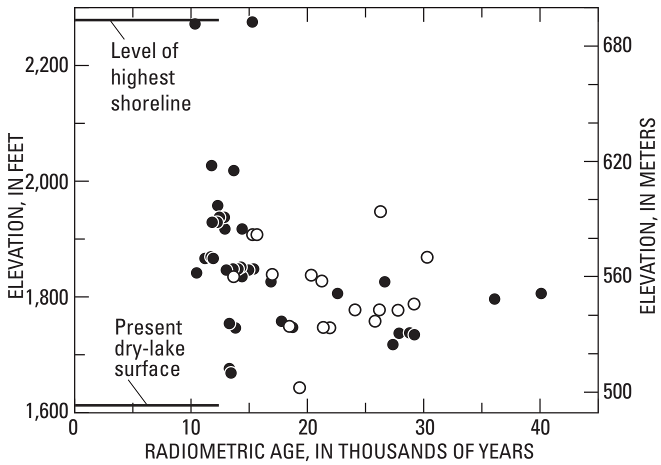


Figure 17. Plot of radiometric ages of dated samples against elevation of sampled outcrop. Data from table 5; dates considered unreliable (enclosed by parentheses in that table) are not plotted. Dots represent sample material, such as tufa, shells, and oolites, that was probably deposited in shallow water; circles represent material, such as marl, that was probably deposited in deep water.

The ^{14}C dates (table 5) from the exposed materials have an uneven record of internal consistency. The probable sources of most errors in such dates are noted by Broecker and Walton (1959, p. 16-18, 21-23), Benson (1978, p. 303-309), Stuiver and Smith (1979, p. 70-73), Benson and Thompson (1987b, p. 243-244), and Benson and others (1990, p. 242-245); sources of large errors in a few dates on marl are discussed below. The most reliable dates on outcrop material from Searles Valley are believed to be those based on the ^{14}C content in (1) organic carbon from sediments and tufas, (2) oolites, and (3) shell material from concentrations of fossil snails and clams that suggest an event that killed much of the living population at one time. A ^{14}C age obtained from a collection of widely scattered shells allows the inclusion of reworked fossils, as in one such sample (unit CD, table 5), introducing the concern that the resulting dates will be too old by an unknown amount.

Somewhat surprising is the finding that dates on disseminated $CaCO_3$ in sediments (marl) appear fairly consistent with other criteria of age in the majority of instances. Dated marl samples as old as 29,000 years show that contamination by younger carbon can be minor. However, dates on marl that appear substantially too old were found when the samples were collected from near the base of a marl bed that overlies coarse sand or gravel. The explanation probably is that these lowermost marl layers were deposited shortly after the re-expanding lake first inundated the sample site. At that time, outcrops of older, unindurated, carbonate-rich marl (deposited during earlier lake stands) were undergoing intense erosion along the nearby readvancing lake shore, and these older calcareous sediments were being transported—and redeposited—a short distance out into the lake. After the lake's shoreline migrated to a more distant location, further up the side of the basin, older clastic carbonate became less abundant at the outcrop location, and the relatively contemporaneous, chemically precipitated carbonate provided most of the carbonate fraction in the sediments. Samples from 0.5 m or more above the base of the marl bed yielded ages mostly consistent with their stratigraphic positions.

Thompson and others (1990, p. 31) observed that dates on dispersed organic matter deposited during shallow stands of Lake Bonneville, Utah, appeared 2 k.y. too old, and similar materials deposited during fresher water intervals provided apparently reasonable estimates. This may be another instance where contamination due to the contemporaneous erosion of nearby sediments, containing one or more forms of older carbon, altered ^{14}C dates.

Dates on dense tufa from the top of unit B and base of unit C are generally consistent, but tufa that was vuggy, heavily weathered, or stratigraphically older produced dates that were somewhat (or a great deal) younger. One greatly contaminated date on ostracode shells from unit B was also too young, as was a date on the enclosing marl (table 5, laboratory nos. W-1894 and USGS-67, respectively).

Many or all of the dates on carbon derived from lake water, including organic carbon, shells, ostracodes, marl, and tufa, from both subsurface and exposed deposits, could be 1,000 or even 2,000 years too old because of the possibility that the CO_2 dissolved in the lake water at the time of deposition was not in equilibrium with atmospheric CO_2 (Broecker and Kaufman, 1965, p. 554; Stuiver and Smith, 1979, p. 70-78). Peng and others (1978, p. 326, tables 3, 9) estimated the average error of this type in Searles Lake salts to be 900 years, based on calculations and comparisons of ^{230}Th and ^{14}C ages from the same horizon in the Lower Salt, but the calculated age discrepancies range from about 400 to 1,100 years, depending on lake area. The magnitude of CO_2 disequilibrium in a lake, however, is also affected by factors such as depth, salinity, and stratification; these change continuously during a lake's fluctuation, meaning that no single correction factor can be applied to dates from all parts of the sedimentary record.

Although one U-series age on the older tufa unit, reported as "greater than 300,000 years," was consistent with its inferred stratigraphic position (described in the section on that unit), others were not. The earliest lithoid tufa deposits in the Searles Lake Formation appear to be stratigraphically equivalent to the basal layers of unit A, yet a sample of tufa from the innermost wall of a 5-m-long adit into one of the large pinnacles gave an age of 31,700 years (table 5, B-86-3). This sample was also dated by the ^{14}C method and found to be "greater than 36,000 years," an age that is compatible with (though not proof of) its correct stratigraphic assignment. Four additional samples of lithoid tufa from unit A that were dated by this method (Garcia and others, 1993) gave results that were not consistent with their stratigraphic position (table 5). In using the U-series dating method on tufa, there appears to be a problem either with the amount of clastic impurities or with contamination or leaching of the original materials by subsequent lakes that repeatedly immersed these porous deposits in younger lake waters that contained new mixtures of the elements and isotopes being measured.

Three samples of altered silicic ash were found in the Upper Salt and Bottom Mud (table 3; Hay and Guldman, 1987), subsurface units equivalent in age to parts of the Searles Lake Formation, but identifiable ash layers were not found in outcrops. This prevented intrabasin or interbasin correlations, as well as possible evaluation of the ^{14}C chronology.

The dated samples listed in table 5 are grouped according to the stratigraphic units from which they come. Each group is interpreted to represent a population of dates that approximate the depositional period represented by a unit. Many of those dates may differ from the true ages of the samples by as much as 1,000—or even 2,000—years because of the error sources noted above; this amount of scatter and overlap in the age ranges of units is not considered significant. However, ages that lie much further outside of the age limits for the unit, as established from subsurface data, are suspect and therefore are enclosed by parentheses in table 5. These ages probably reflect the inclusion of large amounts of reworked carbon from older deposits, contamination of the dated material, or an error in the stratigraphic assignment of the outcrop bed.

A plot of the ages of these dated materials against the elevations of their sources (fig. 17) shows that the history of Searles Lake cannot be determined accurately or in any detail by this method. The highest elevation dates (all on tufa) come from localities where there are no nearby lacustrine sediments to provide stratigraphic context. Although porous tufa is abundant at these upper levels, almost all of it is unsuitable for dating because it contains visible secondary calcite. The best dates came from dense tufa, mollusk shells, or oolites at lower elevations in the basin when the water was shallower. Inasmuch as the remains of algae are found in all tufa samples, and mollusk shells presumably represent species that grazed on algae, deposits including these materials probably represent less than about 10 to 20 m of water, as this is about the maximum depth that the light required for algal growth reaches in most lakes (Ruttner, 1953, p. 12-23, fig. 5).

Figure 17 does show, however, that during the interval between about 15 ka and 10 ka, materials deposited in shallow water are found over an elevation range of about 630 ft (190 m); this aspect of the Searles Lake history is in agreement with the mapped stratigraphy. Prior to 15 ka, lower lake-surface elevations and a smaller range of fluctuations are indicated by the plotted positions of the shallow-water deposits (dots), but the number of dated deep-water deposits (open circles) means that the lake surface was at times also substantially higher.

In view of these uncertainties, the ages assigned in this paper to the timespans represented by the various units of the Searles Lake Formation are clearly approximations. Combining all of the radiometric data available from subsurface and outcrop studies, plus other considerations developed later in this paper, the ages assigned to the units of the Searles Lake formation, and used throughout this paper, are as follows:

Unit D	6.0 ka to ~2.0 ka
Unit CD	10.5 ka to 6.0 ka
Unit C	13.5 ka to 10.5 ka
Unit BC	15 ka to 13.5 ka
Unit B	24 ka to 15 ka
Unit AB	32 ka to 24 ka
Unit A	150 ka to 32 ka.

Fossils

Lacustrine deposits of the Searles Lake Formation contain numerous fossil snails and clams, especially in the Poison Canyon and Salt Wells Valley areas (pls. 3*A* and 3*B*). These regions were near the main source of inflowing fresh water at the times Searles Valley contained large lakes, and the genera and species of snails and clams all indicate low-salinity environments. Rare but widespread snails and clams in the deposits of unit A suggest that the lakes of that time were fresh throughout the valley, presumably a result of voluminous overflow into Panamint Valley. In units AB, B, and C, however, the near-absence of fossils in other parts of the basin seems to indicate that a horizontal salinity gradient existed much of the time.

The earliest published description of fossils from Searles Valley was by Hanna (1963, p. 1-14), although he reports that F.M. Anderson collected specimens from the area some 30 years earlier. Species identified by Hanna came from two localities in Searles Valley (in H24-b and I18-a), and he collected samples containing many of the same species in Panamint Valley (fig. 1). Hanna (1963, p. 4) notes that both valleys contained freshwater lakes when these animals lived. His localities in Searles Valley probably included sediments of subunits sab7 (and sab5?), sc1, sc2, sc3, sc4, and unit CD of the Searles Lake Formation, but his locality data are not specific. For this reason, the identified species are only listed (table 6); to help reconstruct paleohydrologic connections, the species he found in Panamint Valley are also tabulated.

The genera and species of snails and clams found in the lacustrine sediments of Searles Valley after its stratigraphy was determined are listed in table 7. Of them, D.W. Taylor (written commun., July 28, 1966) writes: "All of these mollusks are freshwater forms * * * The snail *Lymnaea kingii* * * *, unknown so far in stratigraphically higher deposits [in Searles Valley] is known from Panamint Valley." This snail's presence in sediments assigned to unit A helps corroborate the stratigraphic and other evidence that Searles Lake overflowed into Panamint Valley during much of the time unit A was being deposited.

Ostracodes are more widespread in Searles Valley, and the genera and limited numbers of species suggest a brackish or saline environment for some collections. Of the abundant *Lymnocythere*, I.G. Sohn writes (written commun., June 22, 1966):

> It is a crawler and burrower rather than a swimmer, and is restricted to nearshore mud and vegetation. * * * The presence of carapaces and growth stages as well as the hydrodynamic difference between the males and females indicate that they were not transported. This suggests no current action. I have no data on temperature. * * * The abundance of one species to the exclusion of other ostracodes is interpreted to indicate a hypersaline environment.

Concerning the ostracode species in samples from the type section of the Searles Lake Formation (figs. 5, 6, table 7), R.M. Forester writes (written commun., Jan. 8, 1988):

> Samples 3, 5, 6, 7, 8, and 10 contain fewer ostracodes and, in general, more poorly preserved ostracodes than is typical for life assemblages in open lacustrine sediments. My guess is that the ostracodes in these samples are most probably reworked from older lacustrine sediments in the basin. When these lakes become large, so that salinities are below 50 to 100 parts per thousand (ppt) and the bottom waters are oxygenated, ostracode productivity becomes enormous. The sand fraction of the sublittoral and profundal sediments is often nearly all ostracode valves. As the lake level falls, these older deposits may be redeposited in the lake by wind and streams. Reworked ostracodes are especially common in the littoral zone of western lakes. The ostracodes from samples 3, 5, 6, and 8 are typical lacustrine taxa suggesting they are reworked from older lake sediments. Some of the taxa in samples 7 and especially 10 are common to the “marsh” facies (ground-water discharge) that surround large lakes and thus suggest reworking from ‘marginal lacustrine’ facies.
>
> Sample 2 contains abundant *Limnocythere sappaensis* together with abundant brine shrimp pellets. This association is common in relatively saline lakes * * * The probable upper salinity tolerance of *L. sappaensis* is around 75 to 80 ppt whereas the lower salinity tolerance of brine shrimp is around 25 to 30 ppt. These tolerances would therefore suggest the salinity was in this range. *Limnocythere sappaensis* is also restricted to carbonate enriched and calcium depleted waters. * * *
>
> Sample 9 contains abundant *Limnocythere sappaensis* and no obvious brine shrimp pellets. Assuming the absence of brine shrimp pellets is a function of original hydrochemistry rather than diagenesis, then the salinity of this lake should be in the range of 5 to perhaps 30 ppt. and thus is lower than for sample 2, discussed above. The presence of pyrite may imply permanence of water and thus perhaps deeper water than would have existed for the lake represented by sample 2 above. The presence of *Limnocythere sappaensis* would, as indicated above, imply carbonate enriched water.

A number of samples from the Searles Lake Formation (as well as older lacustrine units) were examined for diatoms by K.E. Lohman and J.P. Bradbury. None were found. Samples from subsurface lacustrine deposits have also been examined and found barren of diatoms.

Terrestrial vertebrate fossils were sought throughout the study of exposed lake deposits, but none were found. This is in marked contrast with the abundance of vertebrate remains associated with the lacustrine sediments of China Lake (Fortsch, 1978), upstream from Searles Lake during pluvial periods. The relatively high salinity of Searles Lake during its low-level to intermediate-level stages could have discouraged vertebrate animals during those periods, but the absence of such forms in the high and presumably fresh stands, which are also indicated by the mollusks, is puzzling. The abundance of water during the wettest periods, and the relatively steep slopes around much of Searles Lake during its highest stages, might have precluded the development of marshy areas and adjoining grassy plains. These have been postulated (Davis and Panlaqui, 1978) as the favored habitats for animals at China Lake (as well as for early man—also represented by abundant artifacts in the China Lake area, but not in the Searles Lake area).

Table 6. Mollusca described by Hanna (1963) from Searles and Panamint Valleys.

[Symbols as follows: C, common; X, present (or abundance not clearly indicated); R, rare; --, not reported; *, species illustrated in Hanna (1963).]

Mollusk species	Location and abundance	
	Searles	Panamint
Lymnaea kingii Meek	X	C*
Lymnaea palustris (Müller)	R*	--
Physa humerosa Gould	X	X*
Paraphloyx effusa (Lea)	C	C*
Helisoma ammon (Gould)	R*	--
Gyraulus parvus (Say)	C	C*
Carinifex newberri (Lea)	C	C*
Amnicola longinqua Gould	X	C*
Valvata humeralis Say	C*	C*
Succinea rusticana Gould	R*	--
Anodonta cf. *A. californiensis* Lea	R	R
Pisidium sp.	X	X*
Sphaerium cf. *S. striatinum* (Lamarck)	X*	X*

Lithologies of Exposed Units

The lithologies of the several units and subunits of the Searles Lake Formation vary greatly throughout Searles and Salt Wells Valleys. The following discussions provide a general description of each unit, indicate the inferred depositional environment, and outline the nature of any distinctive, unusual, or significant aspects of that unit’s lithologies. More local lithologic details of these units are identified in the explanations of plates 2 to 4. Still further details are provided by the series of measured stratigraphic sections presented in appendix 1, and sedimentological size analyses and statistical param-

Table 7. Fossil mollusks and ostracodes collected from identified stratigraphic units in lacustrine sediments, Searles Valley.

[Snails and clams identified by D.W. Taylor, USGS, Menlo Park, Calif., in May 1966. Ostracodes from localities other than type section of Searles Lake Formation identified by I.G. Sohn, USGS, Washington, D.C., in June and December 1966 and April 1972; ostracodes from type section identified by R.M. Forester, USGS, Denver, Colo., in March 1982 and January 1988.]

Formation, unit, and subunit	Location or number[1]	Faunal group[2]	Identification	Other data
Searles Lake Formation				
Unit D	I5-q	C	*Pisidium compressum* (Prime)	Reworked?
		S	*Vorticifex effusus* (Lea)	Reworked?
		S	*Helisoma newberryi* (Lea)	Reworked?
Unit C	G6-r	O	*Limnocythere*	
	H28-f	O	*Limnocythere*	18 m above base
	H28-f	O	*Limnocythere*	17 m above base
			Candona	
			Candoniella	
	H28-f	O	*Limnocythere*	0.5 m above base
	C10-r	O	*Limnocythere,* aff. *L. inopinata* (Baird)	Fair preservation
	H23-f	O	*Limnocythere,* aff. *L. inopinata* (Baird)	Poor preservation
	10	O	*Limnocythere sappaensis*	Dominant
			Potamocypris n. sp.	Common
			Heterocypris n. sp.	Rare
			Candona caudata	Rare
			Limnocythere paraornata	Rare
	9	O	*Limnocythere sappaensis*	Very abundant, pyrite present
	8	O	*Limnocythere sappaensis*	Reworked
			Limnocythere ceriotuberosa	
Unit B	C30-d	S	*Helisoma newberryi* (Lea)	
	I7-k	C	*Sphaerium transversum* (Say)	
		C	*Pisidium compressum* Prime	
		S	*Valvata humeralis* Say	
		S	*Lymnaea proxima* Lea(?)	
		S	*Gyraulus parvus* (Say)	
		S	*Vorticifex effusa* (Lea)	
		S	*Planorbella subcrenata* (Carpenter)	
		S	*Physa virgata* Gould(?)	
	L8-n	O	*Limnocythere* sp., aff. *L. inopinata*	Females dominant
	C3-h	O	*Limnocythere* sp., aff. *L. inopinata*	Males dominant
Subunit sab7	7	O	*Limnocythere ceriotuberosa*	Variable preservation
			Candona caudata	
			Limnocythere sappaensis	Some reworked?
			Heterocypris n. sp.	Well preserved
			Cytherissa lacustris	Juveniles
Subunit sab6	6	O	*Limnocythere ceriotuberosa*	Rare, well preserved
			Candona caudata	Juveniles, rare
			Limnocythere sappaensis	Reworked
	5	O	*Limnocythere ceriotuberosa*	Rare
			Candona patzcuara	Juveniles, rare
			Limnocythere sappaensis	Reworked
Subunit sab5	4		(barren)	

Table 7. Fossil mollusks and ostracodes collected from identified stratigraphic units in lacustrine sediments, Searles Valley.—Continued

[Snails and clams identified by D.W. Taylor, USGS, Menlo Park, Calif., in May 1966. Ostracodes from localities other than type section of Searles Lake Formation identified by I.G. Sohn, USGS, Washington, D.C., in June and December 1966 and April 1972; ostracodes from type section identified by R.M. Forester, USGS, Denver, Colo., in March 1982 and January 1988.]

Formation, unit, and subunit	Location or number[1]	Faunal group[2]	Identification	Other data
Searles Lake Formation				
Subunit sab4	3	O	*Limnocythere ceriotuberosa* *Limnocythere sappaensis* *Candona caudata*	Low abundance
	2	O	*Limnocythere sappaensis* Brine shrimp pellet coquina	
Subunit sab3	1	O	(barren)	
Unit AB	L8-k	O	*Limnocythere* sp., aff. *L. inopinata* Beard	Females dominant
Unit A	B25-h	S	*Lymnea kingii* Meek *Helisoma newberryi* (Lea) *Vorticifex effusus*	
	C25-n	O	*Limnocythere* sp., aff. *L. inopinata* (Baird)	Females dominant
	C36-e	O	*Limnocythere* sp., aff. *L. inopinata* (Baird)	Females dominant
Christmas Canyon Formation	M33-d	O	*Limnocythere camera* (?)	

[1]Location code as described in "Field and laboratory methods" section of text and in the Index Map on plate 1; numbers refer to horizons labeled on figure 6.

[2]Abbreviations: C, clam; S, snail; O, ostracode.

eters of samples collected from representative outcrops are presented in appendix 2.

Unit A (150 ka to 32 ka)

Unit A of the Searles Lake Formation is correlated with the Bottom Mud in subsurface (table 3), a unit that was interpreted as representing about 100,000 years of mostly deep lakes, with a few periods of intermediate-level lakes (Smith, 1979, fig. 41). Outcrops of this unit are the least well preserved or exposed in the formation, but a few sections of silt, sand, and gravel extending to 2,280 ft elevation and exceeding 25 m in thickness (sec. M19-l, pl. 2*B*; sec. C36-h, pl. 1, and appendix 1) support the interpretation of long periods of deep-water deposition. Massive deposits of lithoid tufa at the highest shoreline along the west side of the valley (cover image and pl. 1) support this conclusion. Thinner sections of unit A are well exposed in most of the canyons along the edges of the Argus and Slate Ranges (pl. 1), especially in sec. H28-j (pl. 3*B*), in secs. H13-c and H26-e (pl. 3*A*), and in secs. I32-r, L8-m, n and K24-b (pl. 4). Many of those exposures, however, are at intermediate elevations where coarse, poorly sorted debris makes up much of the unit, and long periods characterized by intermediate-level lakes also seem confirmed. The huge volume of lithoid tufa near the 1,800-ft level in The Pinnacles area (pl. 4; fig. 18), a unit deposited in an intermediate-depth lake and in large part contemporaneously with the basal part of unit A, supports this inference.

Three types of gravels are included in unit A. The first type, near bedrock, consists of gravels that were transported by longshore currents. Many of these are interbedded with sand or silt, and they are identified as lacustrine deposits by their bedding continuity, fair to good sorting and rounding, absence of disproportionately large cobbles or boulders, and uncommonly low amounts of interstitial silt or fine sand. A variation in this type of gravel deposited by longshore currents is found in secs. K13, 14, 23, and 24 (pl. 1 and pl. 4). There, the fragments form a well-cemented veneer that consists of flaggy slabs eroded from nearby outcrops of older tufa.

The second type of gravel was deposited as lacustrine bars. The largest and best example is the southeast-trending bar that extends from the east end of the Spangler Hills toward The Pinnacles (secs. I31 and I32, pl. 4); it is 5 to 7 m high and 2 km long (table 8; fig. 18). The fragments in it

Table 8. Distribution and characteristics of major lacustrine bars in Searles Valley.

Elevation[1] (ft)	Location		Length[3] (km)	Direction of fragment transport[4]	Stratigraphic assignment[5]
	Plate	Section[2]			
2,260	1	L22-g	2.9	E	sa
2,260	1	N8-d	0.9	NW	sc
2,260	2*A*	A34-a	0.3	E	sc3
2,260	2*A*	A27-h	0.4	E	sc3
2,255	2*A*	A27-h	0.5	E	sc3
2,250	2*A*	A27-j	0.4	E	sc3
2,235	2*A*	A34-h	0.2	E	sc3
2,100	2*A*	C3-r	1.8	E	sab6
2,100	1	L15-q	7.0	W	sab
2,040	3*B*	H21-r	1.4	W	sa[6]
2,040	2*B*	M18-k	0.1	W	scg
2,010	1	L15-m	1.4	W	sc
2,000	1	L19-m	1.6	NW	sb
1,960	2*A*	C10-r	2.7	W	sc1b
1,960	1	L15-e	1.8	W	sc
1,940	1	L18-p	10.1	W	sc
1,920	2*A*	C15-h	4.6	W	sb1,sc1a
1,915	2*A*	C15-j	2.8	W	sb1,sc1a
1,850	2*A*	C15-r	3.7	W	sb1,st
1,790	4	I32-q	2.4	SE	sa1,sa3,sa4
1,710	4	I33-q	0.4	SE(?)	sdg

[1]Elevations are nominal because bar crests vary in elevation by as much as 40 ft (12 m).

[2]Section location indicates a representative segment of bar.

[3]Length listed is for preserved remnant; most bars were originally longer.

[4]Direction as determined at listed locality; some bars have some clastic contribution from opposite side of valley if bar extends that far. Abbreviations: NW, northwest; E, east; W, west; SE, southeast.

[5]Abbreviations for stratigraphic unit(s) as explained on listed plate.

[6]Original bar form apparently determined by underlying sediments of unit A, but horizontal, westerly transport of unit AB fragments that cover inferred sediments of unit A shows that a similar wind regime existed during that later period; deposits of units B and C are also draped over original bar.

all come from the east slope of the Spangler Hills. This bar is very well exposed in both the railroad cut and where an unnamed wash to the southeast dissects it. These exposures show that the gravel facies and bar crest migrated southwestward during its growth. These medium to dark gray gravels are notable for what appears to be a near lack of fine-clastic matrix but abundant calcareous cement. Laboratory size analyses, however, show that many of these gravels have a slightly bimodal size distribution, with minimal coarse to medium sand but greater percentages of (windblown?) fine sand and silt (see appendix 2, table 12). Bedding, which generally dips 5° to 10° northeast, is pronounced. The bar, which has been exhumed, is asymmetrical with a steep southwest side, more gradually sloping northeast side, and flat crest (fig. 18).

The third type of gravel included in unit A is, arguably, not a lake deposit because the fragments were not transported to their present site by the lake. These deposits consist of exposures of older gravels that have had shorelines carved on them by the waves associated with the lake responsible for unit A; gravel deposits assigned to unit A locally overlie them. Excellent examples are found in sections H26-c, L13-L15, M5, and M8 (plates 1, 2*B*, and 3*A*). They are mapped as part of unit A because they document the existence of a lake at that time and at those levels. The processes of carving shorelines has removed the finer fraction of the original gravel, so that its present fragment-size distribution at the surface differs from that of the older gravels prior to their innundation by unit A lake waters.

Sand and sandstone layers in unit A vary greatly in induration. One characteristic form is a very well cemented, or flaggy, sandstone. Most of the exposures of unit A along the Argus Range and Spangler Hills, where coarse-grained plutonic rocks crop out, consist of brownish (5-10YR4-8/2-4), coarse to very coarse granitic sand with angular to subangular fragments that are well sorted and have virtually no fine matrix. A few pebbles are commonly included. Elsewhere, the sands and sandstones of unit A are locally less well indurated, the fragments are mostly medium to coarse sizes, and the colors of some layers are more yellowish (5Y6-8/2-4).

Silt beds, which are not common, may be either very well or poorly bedded and have colors ranging from yellowish to greenish gray (5-10Y6-8/1-4). Silt beds deposited near the paleoinlet are highly calcareous (sec. H23-f, pl. 3*A*; H30-g, pl. 1) whereas those deposited in more remote parts of the valley, especially in the southern part (M18-k, pl. 2*B*), contain small percentages of carbonate.

The outcrop record of this unit is too discontinuous to reconstruct the temporal relation between these high- and intermediate-level stands. In some areas, however, an interbedded alluvial layer is preserved (subunit sa2, pls. 1 and 4); it is not known if these local layers are contemporaneous with each other and thus represent one lake recession, or if there are several layers that represent several recessions. Many examples of these alluvial layers, however, are truncated by a fossil soil that has similar properties (fig. 12*A*); it is a calcareous soil, similar to the one that truncates the Christmas Canyon Formation, but only about 1 m thick, and it commonly has a yellowish orange (10YR6/4-6) zone near its top (sec. K24-p,

Figure 18. Gravel and tufa formed in the time of deposition of unit A of the Searles Lake Formation. Surface in foreground is the near-horizontal crest of The Pinnacles bar, a large lacustrine bar composed at its top of gravel belonging to subunit sa4. All younger, fine-grained sediments of unit B and younger ages have been removed by erosion. Note that bar-gravel lithologies and clast sizes are quite uniform and clasts are mostly angular to subangular. Tower-shaped pinnacles of tufa in background (one-half kilometer and more from the camera), began to grow at about 150 ka and reached elevations as much as 50 m or more above the gravel surfaces. The pinnacles were formed of the lithoid form of calcite ($CaCO_3$), but starting about 30 ka, when deposition of the AB, B, BC, and C tufa members began, they were coated with hard crusts of nodose tufa composed of aragonite (also $CaCO_3$); most of those layers are between 2 cm and 2 m thick.

pl. 4). In one place (sec. I32-r, pl. 4), a 0.6-m lenticular bed of angular alluvial gravel correlated with this subunit and soil is orange-stained throughout.

Areally extensive outcrops of orange-hued boulder alluvial gravels, exposed northwest of Searles Lake, near the mouth of Wilson Canyon, are mapped as alluvial material that is interbedded in unit A. The best examples are exposed in secs. B25-a, C17-e,l,m,n, and C31-l. Local stratigraphic details appear to place them within unit A, but some of the evidence is equivocal. The boulders are commonly 1 to 2 m across, even though they are as much as 3 km from the mouth of the canyon from which they came. Many are also much more intensively weathered than boulders in other areas or from other units (fig. 19). This probably reflects their long and repeated exposure to the destructive forces of wave- and wind-borne, high-pH saline brines. When such brines penetrate cracks in rocks, some solution may occur as a result of the pH (Butler and Mount, 1986), and on drying, expansion and wedging may result from halite's unusually large coefficient of thermal expansion (Skinner, 1966, table 6-1).

Unit AB (32 ka to 24 ka)

Unit AB is correlated with the Lower Salt in subsurface deposits (fig.1*C*), which is composed of seven salt layers separated by mud layers that represent perennial lakes, each of which existed for hundreds of years to a few thousand years. Six of the salt layers represent partial desiccation, one (S-5) represents complete desiccation. These record a lake that fluctuated repeatedly between intermediate and low levels, and the relative thinness of unit AB subunits in all areas except near the main inlet (pl. 3*A*) is compatible with this interpretation.

In much of Searles Valley, unit AB is a coarse alluvial gravel, with its top-surface fragments exhibiting a characteristic light-brown hue (5-10YR3-5/2-6). The larger fragments are mostly angular to subangular; fragment sizes vary but are generally smaller than those in nearby outcrops of the Christmas Canyon Formation or older gravel map units and larger than those in unit BC. In cross section, gravels of this unit have similar hues but lighter values because of their poorly sorted sand matrix. Textures indicative of an alluvial origin include discontinuous and generally poor bedding, wide variation in fragment sizes, fine matrix material in gravel layers, local randomly oriented cross-bedding, and a lack of characteristics indicative of a lacustrine origin.

The lacustrine facies of unit AB all lie at elevations below 2,120 ft. Lacustrine bar gravels, interpreted on stratigraphic grounds to be a part of this unit, are present at this elevation in the southern part of the valley (centered approximately in sec. L14, pl. 1); extensively cross-bedded lacustrine sand, mapped as part of this unit, extends up to about 2,100 ft in the north end of the valley (sec. C3-k,j, pl. 2*A*). The thickest exposed

Figure 19. Large boulders in alluvial gravels mapped as part of unit A (subunit sa2?) are extensively weathered and pitted. The effects of various salts on chemical weathering processes are believed responsible for this morphology, with the salts being introduced by spray from waves of one or more moderately saline lakes when the shoreline was only a short distance away. Weathering as intense as documented by these boulders is not found in most other gravels within the part of Searles Valley once covered by lakes; it is not clear why this weathering product is so stratigraphically limited. Locality: plate 1, sec. C31, at an elevation of approximately 1,900 ft. Bushes in foreground are about 40 cm high.

section of unit AB is in the Poison Canyon area (pl. 3*A*), which was near the main inlet of Pleistocene Lake Searles and thus part of its delta. The type section of the Searles Lake Formation (fig. 6) includes 15.7 m of sediments that are divided into seven separable subunits of unit AB, the maximum resolution of this unit that is possible in the valley. Most of these subunits can be traced about 1 km southeast. Subunits sab2, sab4, and sab6 are silt and fine sand that represent three expanded lakes, and subunits sab1, sab3, sab5, and sab7 represent shallower lakes that probably retreated one or more times until they deposited salines on the lake floor. Several more hiatuses must exist within these subunits of unit AB because its subsurface equivalent, the Lower Salt (table 3), contains seven separate salt layers, indicating that the lake fell to a lower elevation than these outcrops at least seven times.

Although several of the coarser beds in unit AB have orange hues, subunit sab7 is the most intensely colored, commonly approaching light brown (5YR 5/6). Even more intense orange stains are found on the upper 20-30 cm of this bed where it crops out to the west (sec. H23-h, pl. 3*A*) and south (south half of sec. H24-f, pl. 3*A*). The outcrop illustrated by figure 16 also displays this intense staining at the upper contact of unit AB, showing that the angular unconformity between units AB and B was caused by erosion during the retreat of the last deep-water stage during AB time; in subsurface, this stage is designated M-7 (Smith, 1979, fig. 4). That retreat allowed the orange stain to develop on the truncated surface during the short time before the readvance of the lake responsible for deposition of unit B. In the vicinity of The Pinnacles, at 1,720 ft and above, some of the thin gravel layers assigned to unit AB also have a calcareous soil developed on their upper surface (fig. 12*B*), supporting the conclusion that this orange-to-brown color zone is a product of subaerial processes. Development of a thick desert varnish remains as the most likely explanation for this characteristic color. However, the varnish would have had to develop rapidly because no reasonable correlation with dated subsurface sections permits more than about 1,000 years for deposition of S-7, the uppermost salt layer in the Lower Salt (Stuiver and Smith, 1979, fig. 31) and the last episode during AB time when these sediments could have been exposed.

In the elevation range 1,980 ft to 2,080 ft, in the Valley Wells Wash area (pl. 2*A*), exposures reveal two layers of alluvial sediments assigned to unit AB that are separated by a very coarse, angular, well-sorted lacustrine sand. The lower alluvial layer, generally 1-4 m of very pale brown (10YR7/3), poorly sorted pebbly sand, is moderately indurated; it closely resembles the alluvial material in the modern wash. The upper layer is 1-2 m of grayish orange (10YR6-7/4-6), angular pebble gravel and sand that is poorly indurated and fills channels cut in the underlying unit. This contrasting pair of alluvial gravels suggests that the early episode of alluvial deposition of unit AB took place in a climatic setting much like the present, inasmuch as the modern alluvial sediment is so similar in color and occurs in a setting that promoted the development of a heavy desert varnish.

Channeling within unit AB is noted on both sides of a small ridge in one area southeast of the type section (sec. H24-k, pl. 3*A*). The channel, 1 to 2 m deep, is cut in subunit sab6 and filled with orange pebble sand of subunit sab7 (fig. 20*A*), and it aligns with prominent tufa-lined channels cut in gravels of unit A and plotted on plate 3*A*, about 200 m to the southwest (fig. 20*B*). Those channels are thus well dated and appear indicative of a brief climatic episode that generated one or more intense debris flows within this very small drainage area, during deposition of subunit sab7 (see section on Geomorphology).

Because of this demonstrated tendency for unit AB to have notable concentrations of orange-stained fragments throughout, and even more so near its top, this color criterion has been widely used in identifying both lacustrine and alluvial sediments assigned to this unit. It is unfortunate that the process causing this widespread characteristic cannot be described more exactly than by postulating a climatic episode that rapidly produced a thick coating of Fe-rich desert varnish. The conversion of desert varnish to geothite or hematite, the apparent coloring agent, requires only a simple oxidation or hydration process.

Unit B (24 ka to 15 ka)

Unit B is the outcropping equivalent of the lower part of the Parting Mud (table 3) beneath the surface of Searles Lake. The Parting Mud, having a total thickness of 5.4 m in the core studied by Mankiewicz (1975), was subdivided by him into five subunits. The lower two, whose thicknesses account for 3.75 m (69 percent) of the Parting Mud, are here correlated with unit B of the Searles Lake Formation. Using the ages of contacts between the five subunits as estimated by Smith (1979, p. 111), the lower two would represent the span between 24.0 and 15 ka, a period nearly 9 k.y. long. These two subsurface units are characterized by closely spaced dolomite(?) layers, faint (or absent) aragonite laminations, and lighter colors. A shift in the hydrocarbon, terpene, and sterol characteristics at the boundary between these two units, attributed to changing ratios of fossil green algae, blue-green algae, and vascular plant remains, suggests a period of vigorous inflow to the lake until about 17.1 ka, followed by a period of waning inflow (unit BC) until about 12.3 ka. Inflow then resumed, forming a stratified lake that deposited laminated muds (unit C) (Smith, 1979, p. 48, 53, 80). The sense of these reconstructed changes in inflow is notably similar to those inferred in a later section on the basis of changes in the lithologic character of the Parting Mud in core GS-16 and in its CaO and acid-insoluble components, although the inferred ages of the contacts are slightly different.

Outcrops of unit B are widespread in Searles Valley. Its coarser facies mostly consist of rounded to subangular gravel or sand, with common fragments of nodose tufa. The light to dark gray gravels are mostly well sorted and contain relatively little clastic material in their matrix, but they commonly are well cemented by massive calcite. Fragment sizes in bar and beach deposits include pebbles, cobbles, and small boulders. Extensive gravels composed of small, light-gray pebbles characterize deposits of this unit throughout a large region south and southwest of The Pinnacles (pl. 4). Gravel facies are mapped separately from silt and sand facies on plates 2 to 4.

Medium to coarse sands assigned to unit B tend to be greenish or tan and are well sorted with little finer matrix. Fine sand, silt, clay, and marl beds range in color from very light tan to greenish or slightly orange. Bedding, defined by color or grain-size change, is most commonly faint or absent; laminar bedding caused by color or mineralogic change is found locally, but white laminae are less common and are more widely spaced than in sediments of unit C. The calcareous component of the marl, silt, and clay consists of aragonite, calcite, and dolomite, but calcite dominates in most samples. Ulexite and gypsum occasionally are seen in this unit (sec. H23-g). In the Salt Wells Valley (pl. 3*B*) and Poison Canyon (pl. 3*A*) areas, most of the silt deposits assigned to unit B contain conspicuous quantities of yellow-green mica flakes. Cauliflower-shaped growths of brown nodose tufa are abundant near the top contact of unit B in many areas, especially in the vicinity of Poison Canyon.

Unit B varies in thickness from a fraction of a meter to about 20 m. The thickest sections are on the north side of the Poison Canyon area (pl. 3*A*), although at the type section of the Searles Lake Formation, on the south side of this area, the entire unit was removed by sublacustrine erosion. Thicknesses of 2 to 3 m are common: In the southwestern part of Searles Valley, 2 to 3 m of pebble gravels and greenish silts assigned to unit B crop out over extensive areas; along the flanks of the Argus and Slate Ranges, 2 to 4 m of sand and pebble to cobble gravels represent the unit; east of The Pinnacles, 3 to 4 m of silt and sand are mapped as part of this unit; and along Randsburg Wash, 1 to 4 m of greenish sand and silt are exposed.

Although sediments assigned to unit B extend to the 2,280-ft level, some evidence suggests that the lake responsible for unit B underwent considerable fluctuation. Exposures of sediments mapped as unit B along Randsburg Wash, near the 2,000-ft contour (pl. 2*B*), include layers of sand and gravel that appear to be alluvial but could be turbidites; exposures of silt near this elevation in the middle of the southwestern arm of this valley have several interbedded layers of sand. Exposures of unit B east and northeast of the Spangler Hills, between elevations of 1,630 ft and 1,720 ft, have been divided into six subunits (pls. 3*A* and 4), each of which is a bed of silt, as much as 2 m thick, overlain by a thinner sheet of lacustrine sand. This suggests deposition occurred during relatively long periods of deep lakes that were interrupted by brief periods characterized by shallow lakes whose surfaces were not much above the 1,720-ft contour level.

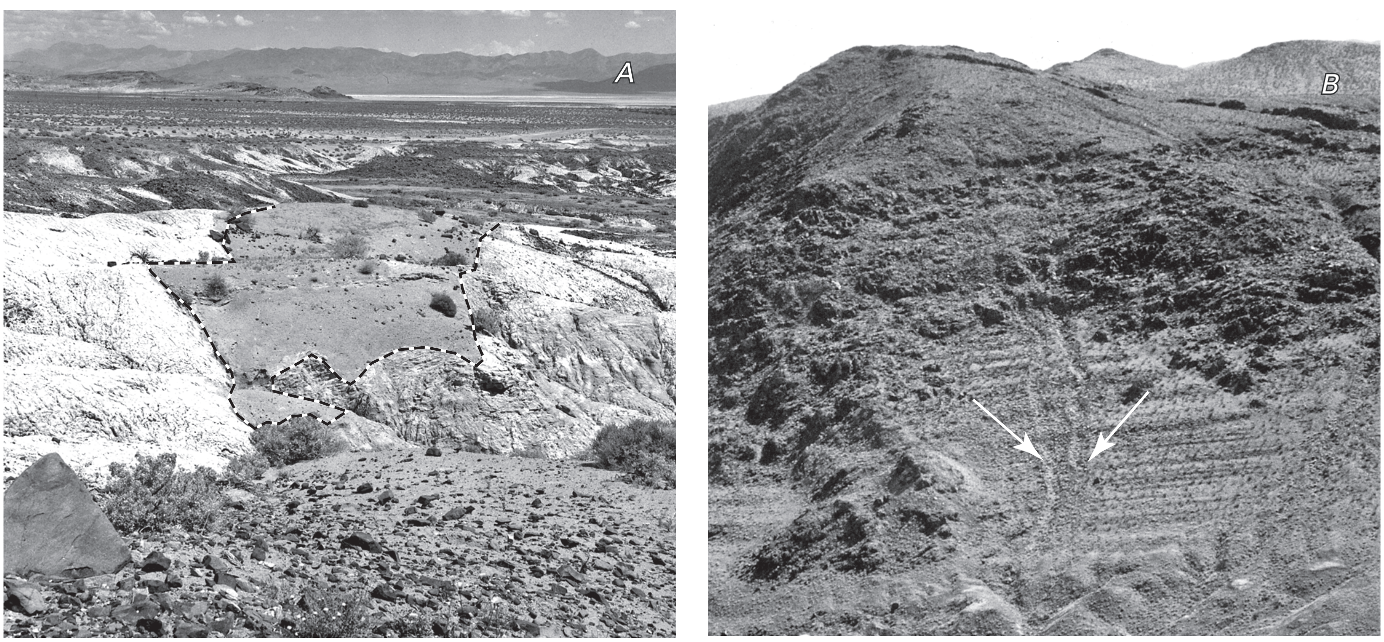


Figure 20. Eroded and filled channels formed during the time of deposition of unit AB. *A*, Exposure of channel (outlined by dashed line) eroded in silt of subunit sab6 (light gray) and filled with sand of subunit sab7 (medium gray); channel width about 3 m, depth 1 to 2 m. View to northeast; location: plate 1, sec. H24-k. *B*, Aerial view of two channels (arrows) on east end of Spangler Hills that are cut in shoreline gravels of unit A and align with filled channel shown in *A*. The small drainage collection area indicates that a very unusual weather event produced the volume of water required to erode these channels (see text). The channels, 3 to 5 m wide, are lined by levees, whose tops are about 2 m above the channel floor; the levees are built of boulder-size fragments. Channel floors are coated with nodose tufa, showing that no major amounts of water carrying coarse sediment have reoccupied them since the channels were formed during the interval between deposition of subunits sab6 and sab7. View to west; location: plate 1, sec. H24-q.

Unit BC (15 ka to 13.5 ka)

Unit BC of the Searles Lake Formation is correlated with a 0.9 m section in the Parting Mud (table 3), as subdivided by Mankiewicz (1975). This section was interpreted by him to represent the period extending from 14.5 to 12.3 ka, a period 2.2 k.y. long; the ages used elsewhere in this paper reduce its duration to 1.5 k.y. The lithology of this part of the Parting Mud in cores is laminated marl, but the laminae are more widely spaced than in the overlying two subsurface units, and they are more frequently orange (dolomite?) than white (aragonite). The near absence of subsurface salines at this horizon suggests that while the depositing lake may have shrunk, its depth was always more than about 130 ft (40 m), the estimated maximum depth at which salts could have begun to precipitate in the winter from solutions having salinities near 13 percent (Smith, 1979, fig. 32). This would indicate lake levels near the 1,660 ft contour. However, alluvial, soil-bearing sediments assigned to unit BC can be traced locally down to the 1,630-ft level (table 9), meaning that for a period, some salts probably crystallized, as suggested by traces of trona and borax at about this horizon in a few cores (Smith, 1979, fig. 24), but that virtually all of those salts dissolved when the lake again expanded.

In many parts of Searles Valley, unit BC is an alluvial or colluvial gravel. The alluvial gravels have maximum fragment sizes that range from cobbles to boulders, with a matrix composed of poorly sorted pebbly sandstone. Bedding, when present, is discontinuous. Colors on fresh surfaces are tan or brownish orange; on weathered surfaces they are commonly moderate brown (5YR 4/4). Colluvial gravels, mostly 0.3 to 1.0 m thick, are composed of pebbly sand or silt. In some areas, a high percentage of the pebbles are nodose tufa. It might appear that some of the deposits assigned to unit BC should be mapped as unit B, because lake waters were required to introduce some of the fragmental components that do not crop out uphill from the colluvial deposit and contacts between units B and BC are commonly gradational. However, in-place reworking of thin beds of unit BC gravels that incorporated material from underlying deposits assigned to unit B would also be an adequate explanation for the anomalous fragment content of these sediments. In most areas, the unit separates lacustrine sediments that are assigned to units B and C.

At elevations below about 1,860 ft, unit BC is also commonly a lacustrine sand (fig. 15). Unit C once covered all of these deposits, but unit BC has been exhumed over large areas in the northwestern and eastern parts of the Poison Canyon area (pl. 3*A*), where the deposits of unit BC were uncharacteristically thick because they were deposited as a delta into the shrinking lake. Especially good exposures of this facies of unit BC occur where excavations were made for the railroad tracks adjoining the east edge of the area of plate 3*A* (I17-d,e,m,n), and along the north side of the amphitheater (such as H14-r); outcrops interpreted to represent the transition from alluvial to lacustrine facies are found in secs. H22-a,h and H23-d,e. Away from outcropping bedrock, this lacustrine facies of unit BC most commonly consists of medium to very coarse sand, subangular to subrounded and fairly well sorted. Pebbles are locally common. Grayish orange hues (5-10YR5-7/3-6) characterize most exposures, and some show deltaic bedding on a massive scale. Thicknesses of this facies vary from less than 10 cm to 2 m, and changes in thickness occur over short distances.

A distinctive and moderately well developed soil formed on the surface of unit BC (and older units exposed at the close of this time period). This soil was useful as a diagnostic criterion when mapping and is referred to herein as the BC soil. It consists of a zone about 30 cm thick, with semi-indurated pods of white calcite, 1-2 cm across and 2-5 cm apart, throughout the lower 25 cm of the soil (fig. 13*A*). Some profiles reveal a moderate concentration of clay, but others appear to be nearly clay-free. A diagnostic (and unexplained) characteristic of the soil is the presence of a network of very irregular, hairline-size, moderate red (5R4-6/6) streaks; they are visible on and within the calcite pods, form networks on the surfaces of pebbles, and can be traced through the silt or sand matrix material. These marks look like remnants of rootlets of some plant, but no remnants of roots were found attached to them. No plant was identified whose roots would produce this unusual color, although desert holly (*Atriplex hymenelytra*) flowers have colors near this hue (though not intensity), showing that the shrub contains the necessary components to produce the color. A similar, but thinner and less intensively developed, soil also formed on the surface of unit CD (fig. 13*B*), and care had to be exercised in using the BC soil as a correlation tool during mapping.

The soil on unit BC is remarkable because it appears that only about 1,500 years was available for both deposition of this unit and development of this soil; the lake's recession period might have been at most 2,000 or 3,000 years, but even these lengths of time seem short for both steps to have taken place. Compounding the problem are exposures of this soil on exhumed surfaces of unit BC near the 1,640 ft contour, only 25 ft above the present dry lake surface (sec. F31-n); this would require the lake to have been below this level for a period long enough for the soil to develop. This one exposure might be an anomalous occurrence of the younger CD soil, but the BC soil is developed on many alluvial sediments below 1,700 ft elevation that are tied to apparently reliable stratigraphy, meaning that the lake stood at levels below this elevation for a substantial period.

One reason that weak calcic soils could have developed rapidly in this region is the abundance of salty and calcareous sediment that was exposed to wind transport. Salt accelerates the fragmentation of mineral grains and thus increases the area exposed to rock-water reactions that can form pedogenic clays. Calcareous dust was—and still is—transported to all parts of the valley by wind, allowing rapid accumulation of the ingredients required for the observed calcareous horizon. Chadwick and Davis (1990, p. 243) present strong evidence of the importance of eolian dust as a source of fine materials and salts (which accelerate weathering rates) in late Pleistocene

Table 9. Elevations and representative locations of exposures mapped on plates 1 to 4 that document highest levels of lacustrine sedimentation (**bold** type) and lowest levels of alluvial sedimentation (light type), Searles Lake Formation.

Unit	Map label	Elevations and locations on plates[1]					
		Pl. 1[2]	Pl.2*A*	Pl.2*B*	Pl.3*A*	Pl.3*B*	Pl.4
D	sdg	**1,800** G6-c	--	--	**1,800** H24-k	--	**1,720** I30-k
	sd	**1,740** J28-n	--	--	**1,810** H23-f	--	**1,790** H31-h
CD	scd	1,630 I8-a	--	--	1,645 I8-f	--	1,700 I34-e
C	sc4	--	--	--	**1,700** I18-h	--	--
	sc3	--	**2,280** A28-e	--	**1,920** H23-e	**2,080** H21-m	**1,930** L18-l
	sc2	--	1,940 C15-d	--	**1,870** H23-b	**2,080** H20-j	--
	sc1	--	**2,270**[3] A35-d	--	**1,920** H23-f	**2,030** H20-r	**1,940** L18-n
	sc	**2,280** M17-p	--	**2,050** M18-k	--	--	--
	scg	--	--	**2,280** M17-n	**2,200** H25-h	--	**2,280** K1-a
BC	sbc	1,630 I6-j	--	1,850 M6-l	**1,910** H23-e	--	1,630 I28-a
	sbcg	--	--	--	1,660 I8-e	--	--
	sbc2	--	2,020 C11-e	--	--	--	--
	sbc1	--	1,860 C15-l	--	--	--	--
B	sb6	--	--	--	**1,880** H23-c	--	**1,680** I19-p
	sb5	--	--	--	**1,870** H23-c	--	**1,675** I19-p
	sb4	--	--	--	**1,840** H14-r		**1,670** I19-q
	sb3	--	--	--	**1,820** H14-r	--	**1,720** I32-e
	sb2	--	**2,150**[4] A34-r	--	**1,810** H14-r	--	**1,670** I30-h
	sb1		**1,820**[4] C23-e	--	**1,800** H14-r		**1,715** I32-e
	sb	**2,280** C4-m	--	**2,060** M18-r	**1,960** H13-d	2,030 H21-r	**1,970** L19-g
	sbg	--		**2,260** M19-f	**2,280** H26-h		**2,260** L6-d
AB	sab7	--	1,850 C14-n	--	**1,970** H23-r	--	--

Table 9. Elevations and representative locations of exposures mapped on plates 1 to 6 that document highest levels of lacustrine sedimentation (**bold** type) and lowest levels of alluvial sedimentation (light type), Searles Lake Formation.—Continued

Unit	Map label	Elevations and locations on plates[1]					
		Pl. 1[2]	Pl.2*A*	Pl.2*B*	Pl.3*A*	Pl.3*B*	Pl.*4*
AB	sab6	--	**2,110** C3-k	--	**1,960** H23-r	--	--
	sab5[5]	--	1,840 C-15p	--	**1,810** H24-c	--	--
	sab4	--	--	--	**1,760** H24-e	--	--
	sab3	--		--	**1,850** H23-c	--	--
	sab2	--		--	**1,830** H23-c	--	--
	sab1	--		--	**1,810** H23-c	--	--
	sab[6]	**2,100** L21-1	--	**2,120** M18-m	--	**2,010** H28-e	**1,840** L8-k
	sab[7]	1,700 I36-m	--	1,850 M6-m	--	1,920 H28-e	1,710 I33-l
A	sa4		--		--	--	**1,840** I31-h
	sa3	--	--		--	--	**1,980** K13-p
	sa2	--	--		--	--	1,770 I32-r
	sa1	--	--		--	--	**1,970** K24-f
	sa	**2,280** L24-a	**2,250** A27-r	**2,260** M30-n	**1,800** H23-f	2,180 H28-8	--
	sag	--	--	**2,280** M19-d	**2,280** H26-c	--	**2,280** L6-e
	saa	1,660 F32-l	--	--	--	--	--
Tufa	st	2,280 K22-e	1,890 C15-k	2,220 M19-l	2,260 H26-b	2,030 H28-l	1,990 L19-h

[1]Elevations in feet above mean sea level; section labels as explained on plate 1 and in text.

[2]Locations cited on plate 1 are only those outside of areas shown on plates 2 to 4.

[3]Includes map units scla, sc1b, sc1c, and sc1d

[4]Subunits sb1 and sb2 on plate 2*A* not equivalent to subunits with same numbers on plates 3*A* and 4.

[5]Subunit sab5 on plate 2*A* correlated with subunits sab1, sab2, sab3, sab4, and sab5 on plates 3*A* and 4 (see table 2).

[6]Lacustrine sediments, undifferentiated.

[7]Alluvial sediments, undifferentiated.

soils that are imbedded in deposits of Lake Lahontan, Nevada; the eolian flux came largely from lake deposits that became exposed when the lake retreated, and the amount of dust was proportional to the percent of upwind area exposures, resulting in areally variable, but accelerated rates of soil formation during these dry periods. Machette (1985, p. 8) documents the amounts of aeolian carbonate accumulating and contributing to the soils in New Mexico, and he further notes the large amounts of dissolved Ca found in rainwater (which also contains dissolved CO_2). In Searles Valley, where virtually all the fine lacustrine sediments exposed at the surface contain 5 to 10 percent $CaCO_3$, both mechanisms could have created an abnormal flux of both dissolved Ca and particulate $CaCO_3$.

Unit C (13.5 ka to 10.5 ka)

Unit C is the outcropping equivalent of the upper two subdivisions of the subsurface Parting Mud as proposed by Mankiewicz (1975), plus a thin overlying third layer described by Smith (1979, p. 51). Mankiewicz's two subdivisions, which together are 0.75 m thick, are finely laminated and contain large gaylussite and pirssonite crystals. They represent a period of time estimated by him to extend from 12.3 ka to 10.5 ka (Smith, 1979, p. 73, 111-112), about 1.8 k.y.; the ages used in this paper (13.5 ka to 10.5 ka) increase the length of this period to 3.0 k.y.

Outcrops of unit C are found at elevations up to 2,280 ft in Searles Valley. The gravel facies, deposited as beach deposits near bedrock, and as bars elsewhere, are similar to those of unit B, except finer in the same depositional setting. Gravel facies are mapped separately on plates 2 to 4. Most fragments are subangular to subround, and the deposit surfaces are dark gray except for brownish-orange bar and sheet gravels assigned to unit C at elevations between 1,840 and 1,960 ft (pl. 2*A*) in the Valley Wells Wash area. A bar of this age and at 1,960 ft in the southern part of Searles Valley is light brown. Above about 1,960 ft, few gravel bars of this age are found.

Near the highest shoreline levels, the bar deposits mapped as parts of unit C are composed of sand. The best examples are in sec. A27-g,h,j (pl. 2*A*); less well developed bars at this elevation crop out in secs. N6-r and N8-d,e (pl. 1). The sand is moderately well sorted, subangular to subround, and most commonly in orange- or yellow-tan hues (5Y-10YR6-7/1-4). Bedding is fair to poor in most outcrops. Where not in the form of bars, sand layers assigned to unit C are mostly fine to coarse, well bedded, moderately indurated, calcareous, and tan to slightly orange or pink in color. Small mollusks are present in some beds.

Throughout virtually all of the Searles Lake basin, silt, clay, and marl deposits of unit C are thinly bedded and flat-lying (figs. 21*A* and *B*), and virtually all are thinly laminated (fig. 10). Laminae are less distinct and sometimes missing in fine sediments exposed along the east side of Searles Valley, but elsewhere they are a reliable indicator of fine sediments belonging to unit C. Laminae are most commonly nearly white and range in thickness from paper-thin to about 3 mm, but 1-mm layers represent an approximate average. The layers separating these laminae are pale olive (10Y6/2) and typically several times thicker than the white laminae. Outcrop samples have high concentrations of aragonite in the white laminae, but calcite is detected. (In subsurface, white laminae are composed of pure aragonite; see Smith, 1979, p. 48, 51.) Dolomite is also a common constituent in outcrops of fine sediments from this unit, and megascopic gypsum crystals are present in subunit sc1 in many areas. Gaylussite crystals are present in outcrops at one place (sec. I23-p). The unlaminated subunit sc4 (pl. 3*A*) is typically dusky yellow green (5GY5/2), massive, and when moist (as it commonly is) has the plastic properties of modeling clay.

Nodose tufa deposits are found both at the base of, and within, sediments of unit C. Basal tufa deposits cannot be distinguished from those deposited during the late stages of deposition of unit B, so ^{14}C dates on samples from this horizon mostly scatter between 15 ka and 12 ka. However, tufa coating the surface of a channel that appears to have been eroded just prior to deposition of 20 m of sediment correlated with unit C (H28-e,f, pl. 3*B*; fig. 21*A*) provided nearly identical dates (12,700±60 and 12,910±50 yrs) on carbonates. In the southern part of the basin (sec. L18-r, pl. 4), tufa whose carbonate and organic carbon content were dated at 12,200±450 yrs and 11,720±500 yrs, respectively, preceded the construction of a prominent bar during unit C time. The carbonate in tufa 10 km to the east (sec. L12-r), dated at 12,110±30 yrs, preceded deposition of the same bar. A thin bed of nodose tufa that lies about 1 m up from the base of unit C (fig. 21*B*) and persists throughout much of the Poison Canyon area (pl. 3*A*) is dated as 13,300±500 yrs. Unit C contains thin beds of tufa in many other areas, showing that lake chemistry during this period was favorable for tufa growth.

The sediments assigned to subunit sc4 appear to have acquired their plastic properties soon after deposition. Soft-sediment deformation of this unit, well exposed in sec. I18-a (pl. 3*A*; fig. 22), locally produced near-vertical attitudes of beds. The underlying deposits of subunit sc3 are scarcely deformed, although they were eroded subaerially prior to deposition of subunit sc4.

In spite of the small amount of time allocated to the deposition of unit C, it is widespread in Searles Valley. It undoubtedly once covered virtually the entire floor of Searles Valley below the 2,280 ft contour. Preserved thicknesses vary greatly, with 5 to 20 m exposed in the western part of the basin near the paleoinlet (pls. 3*A* and 3*B*), and 1 to 3 m in the south half of the basin. In the northern part of the Valley Wells Wash area (pl. 2*A*), bars assigned to subunits sc1 and sc3 are composed of 5 to 8 m of very coarse sand and pebbly sand that was largely derived from the weathering of plutonic rocks in Great Falls Basin (secs. B12, B13, C7, pl. 1).

Unit CD (10.5 ka to 6.0 ka)

Unit CD of the Searles Lake Formation is equivalent to the subsurface Upper Salt (table 3), and it is thus of early Holocene age. Whereas the Upper Salt is typically 15 m thick,

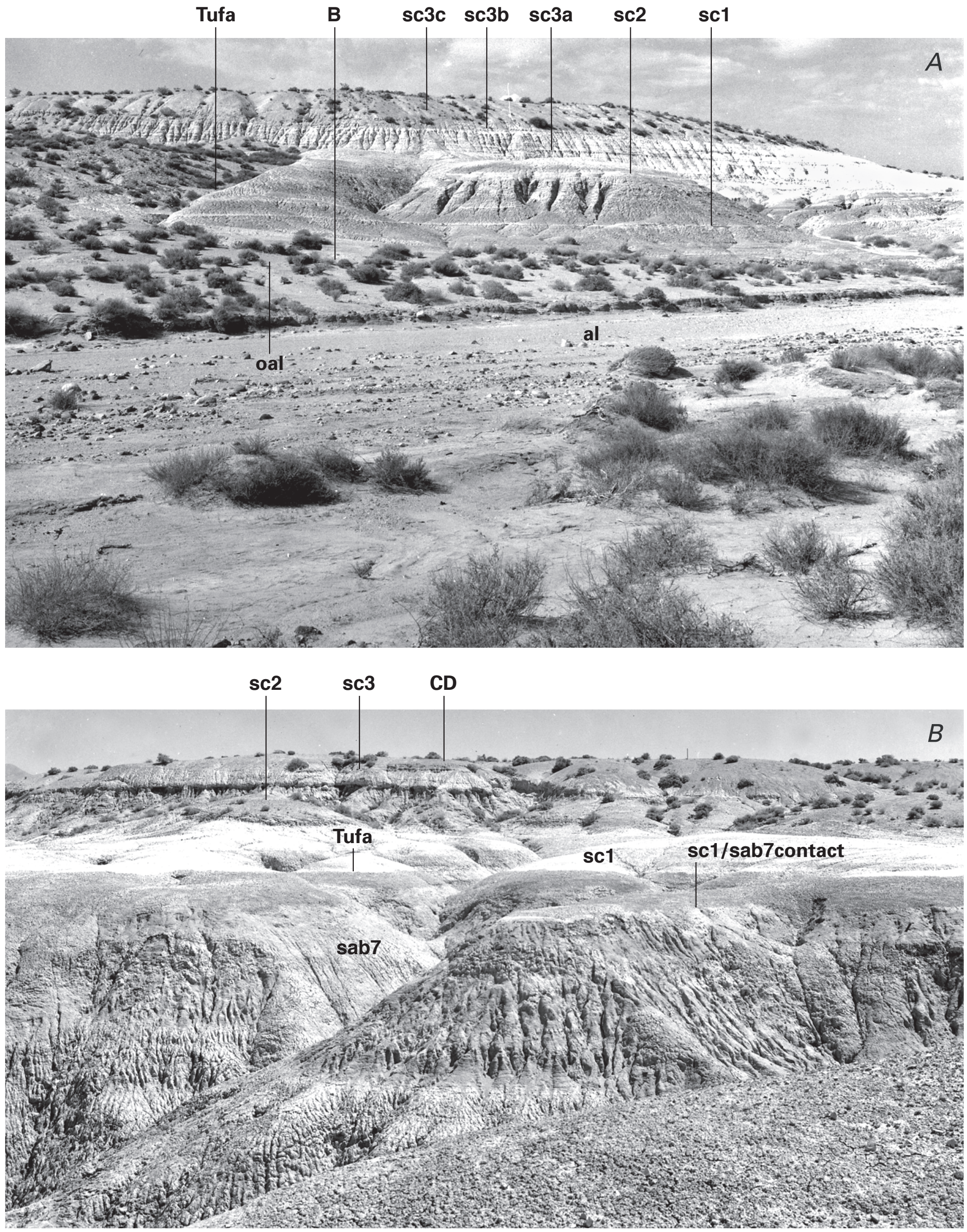


Figure 21. Two outcrops that include thick sections of unit C of the Searles Lake Formation. *A*, View north from California Highway 178 of sediments exposed 1.6 km (1 mi) west of the upper end of Poison Canyon (pl. 3*B*; see also appendix 1, measured section H28-f); unit B and subunits sc1 to sc3c are labeled on the photograph. Unit BC is missing; units older than unit B are covered by older inactive alluvium (oal), and active alluvium (al). A thin bed of nodose tufa (labeled) covers an erosional 30° slope formed after deposition of subunit sc2 and before deposition of subunit sc3a. That tufa yielded ^{14}C ages of 12,700±60 and 12,910±50 years B.P. *B*, Sediments exposed on south side of California Highway 178 at type section of Searles Lake Formation (see fig. 6). Deposits of unit C rest on flat erosional surface underlain by subunit sab7, which was exposed when sublacustrine erosion removed overlying deposits of units B and BC. Flat zone of nodose tufa (labeled), about 1 m up from base of subunit sc1, was traced 150 m northeast and sampled for ^{14}C dating, yielding an age of 13,300±500 years B.P.

unit CD in most of the areas shown on plates 1, 3*A*, 3*B*, and 4 consists of only a few meters of sediment; locally, where units C and D are mapped as being in contact (sec. I16 and I21, pl. 1), it is a sand layer as thin as 2 cm.

This alluvial unit was deposited at the time the last of the lakes responsible for unit C was retreating. In many areas, unit CD is perched on the tops of ridges, resting on very slightly eroded surfaces underlain by sediments of unit C. There, alluvial sediments must have followed the retreating lake, before the development of a network of alluvial channels at lower elevations diverted the remaining inflow and its sediment away from those abandoned surfaces. Most alluvial deposits of unit CD in the Poison Canyon area (pl. 3*A*) are pebbly sand or pebble gravel, 1 to 3 m thick. Outcrops are tan or slightly orange, and a thin pebbly lag gravel commonly is present on the top surface. Reworked mollusks are noted locally. A fossil soil, present in some areas, is similar to the BC soil, but this CD soil is generally thinner, the calcite nodules are smaller, the clay content is very small or missing, and the red root(?) marks are less prominent. In most of the Poison Canyon area, unit CD is 1 m to 3 m thick, but its base rests in part on a channeled surface, with channel depths ranging from less than 1 m (fig. 6) to about 8 m (fig. 22); these channel depths are locally added to the more typical unit thickness. Erosion preceding deposition of unit CD in the channeled area extended to depths below that of the present wash, yet the smooth upper surface of unit CD in that area has a steeper gradient than the present alluvial surface and lies more than 10 m above it. This erosion could have been the result of a short (single?) episode of renewed overflow from China Lake after Searles Lake had nearly desiccated. Very shortly thereafter, more than 10 m of unit CD alluvium buried the channeled surface as Searles Lake continued to recede.

Deposition of unit CD is also responsible for a somewhat coarser, exhumed deltaic fan near the edge of Searles Lake and east of the railroad tracks (sec. I8, pl. 1). There, unit CD is more than 2 m thick in places and rests on subunit sc4; silt and thin gravel mapped as unit D overlie its east edge. Along this contact to the southeast (sec. I16-c; pl. 1), unit CD thins to a sand layer only 2 to 20 cm thick.

On the east end of the Spangler Hills (secs. I19-p and I30-c,f,g, pl. 4), two fans composed of coarse boulder alluvium derived from the upstream canyons are mapped as unit CD (fig. 23). The alluvium rests on the nearly undissected beds of subunit sc1 and is overlain by both the fine and coarse facies of unit D. Although the lake responsible for unit D rose to the 1,800-ft contour, covering most of these fans, stillstands at that and lower levels must have been brief, because shorelines were not developed. Modern alluvium occupies channels cut about 1 m deep in these deposits of unit CD.

In areas 3 to 11 km east of The Pinnacles, remnants of unit CD are found as caps on as much as 5 m of dissected sediments mapped as units B and C. The gravels are alluvial, with maximum pebble sizes of about 2 cm; the CD soil is present on some remnants. However, to the north and northeast of these dissected areas (starting at about sec. J29), and south nearly to the Garlock Fault, outcrops of unit CD descend nearly to the same grade as modern alluvium, and the gravels of this unit constitute most of the slightly dissected alluvial fan surface along the south half of the Slate Range. In these areas, the fragments are also angular but larger than those in modern alluvium; the largest are about 30 cm across and the average is near 5 cm. Most fans are medium dark gray, because the fragments are mostly metamorphic rocks and little desert varnish has developed on them. Below 1,800 ft elevation, but not above it, many of the schistose fragments on the surface of the deposits mapped as unit CD are spalled, apparently the result of salt wedging during stands of the saline lake responsible for unit D. As on the fans of this age exposed east of the Spangler Hills (fig. 23), shorelines were not developed by that younger lake in these areas, and the CD soil is preserved in only a few places. Downhill, the gravels of unit CD appear to be overlain by finer gravels mapped as the gravel and sand facies of unit D, although the stratigraphic relations along this contact are subtle.

Unit D (6.0 ka to ~2.0 ka)

Unit D, of middle Holocene age, occupies a larger percentage of the mapped area (pl. 1) than any other Cenozoic deposit. It is the lateral equivalent of the informally named Overburden Mud in subsurface studies (Smith, 1979, p. 66-68), which core logs show to be composed of mud (moist, dark green, pirssonite-bearing clay, silt, or sand) beneath the edge of the dry lake and discontinuous beds of mud alternating with salines (halite and several other evaporite minerals) beneath its center. Core logs describe many of the saline layers as impure, poorly consolidated aggregates of euhedral to anhedral crystals, although some of these are interbedded with thin zones of pure, coherent crystal masses that are locally vuggy. A ^{14}C date on wood from a depth of 2.4 m (Stuiver and Smith, 1979, p. 73) indicates its age at this level to be near 3,500 years.

This unit was deposited in a lake that rose to about the 1,800-ft contour. Lacustrine silts and gravels identified as part of this unit are found in many areas, especially southwest of Searles Lake, and they are traced uphill to the 1,800-ft contour in two areas: In sec. I31-h (pl. 4), deposits of the sand and silt facies are preserved, and in sec. H24-k, q (pl. 3*A*), lacustrine gravels of the gravel and sand facies can be traced to the 1,800-ft contour, where they grade into angular-boulder alluvial gravels that extend almost to the 2,000-ft contour. These outcrops thus document a lake that was more than 200 ft (60 m) deep when its floor was at an elevation near 1,600 ft. A nearshore bar, 1 to 2 m high and composed of sandy gravel, is found near the 1,720-ft contour in one area (I33-q, r, pl. 4).

Outcrops of unit D are divided on plate 1 into three facies and on plates 3*A* and 4 into two facies. Weathered surfaces of the sand and silt facies are characterized by loosely compacted clastic materials that weather with puffy surfaces, have thin halite efflorescences, and contain (rarely) small buried pods of ulexite. Their color systematically approximates grayish

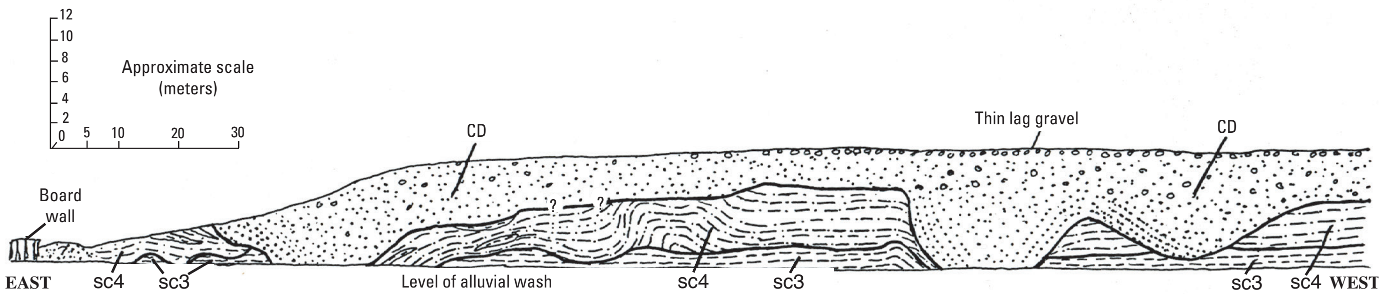


Figure 22. Field sketch of exposures of Searles Lake Formation that document soft-sediment deformation of subunit sc4 and subaerially eroded channels cut on tops of both subunits sc3 and sc4. Deposits of unit CD subsequently filled those channels. Location: plate 1, sec. I18-a.

orange (10YR7/4). Fresh surfaces are commonly very well cemented by halite, as is much of the underlying 10 to 20 cm of sediment of units B and C. When outcrops of the sand and silt facies of unit D are traced from the outermost edges of Searles Lake toward its center, they become first a zone of moist, sticky, and soft mud on which it is impossible to drive (or locally, to walk), then they become a zone of halite-rich silt of varying shades of gray or brownish gray that has a tendency to form polygonal cracks and crusts that produce irregular surfaces (Smith, 1979, fig. 29), and finally they grade into the salt facies of unit D (pl. 1), which is smooth, slightly muddy, yellowish gray (5Y6-8/1) halite that is hard and coarsely crystalline. The contact between the salt facies and the surrounding halite-rich silt segment of the sand and silt facies, however, is gradational—almost hypothetical—because the properties of the surface layer change so gradually from one to the other; Haines (1959, fig. 6) plotted the approximate position of this transition as shown on plate 1.

Above the 1,760-ft contour, the gravel and sand facies of unit D (unit sdg; pls. 1, 3*A*, and 4) is a deposit generally less than a meter thick composed of angular to subangular pebbles or cobbles that weather to shades of dark orange-brown or black and are locally separated by a silt matrix. Below 1,760 ft, the deposit consists in most places of a very thin gravel layer that is always either the uppermost or only bed of unit D. Fragments in it are similar but smaller, and they may form a widely scattered one-pebble-thick pavement (fig. 24). Where shown on plate 1 around the edge of Searles Lake, this facies mostly consists of a zone of lag gravel—concentrations of pebbles and small cobbles scattered upon the surface of the sand and silt facies. Near Argus (sec. F19-a,b), this facies consists of boulders as large as 0.5 m. Although the coarse fragments account for only a small fraction of the exposed material in these areas, they are mapped as part of this facies because they extend as much as a half kilometer further onto the dry-lake surface than any other coarse layer in this unit. These deposits appear to record a brief—quite possibly, a single—climatic event of uncommon intensity that transported angular alluvial gravels far into the lake, which then redistributed them laterally, parallel to its shore. This event probably occurred during the final stages of unit D deposition.

In secs. J29-q,r and J32-a (pl. 1), an area where schistose rocks from the Slate Range make up much of the alluvial and nearshore lacustrine sediment mapped as unit CD and the gravel and sand facies of unit D, many of the schistose pebbles and cobbles between about 1,700 and 1,800 ft elevation are partially split along their planes of schistosity. This splitting appears to be a product of the wedging action of subaerially crystallizing halite, where its dissolved components were repeatedly introduced by fluctuating lake levels or by splashing waves. This provides additional evidence of the high salinity of the lakes that deposited unit D.

In the area between the Spangler Hills and Searles Lake, deposits of unit D commonly rest on small terraces along the sides of the modern drainages. In numerous examples, the terrace level is about halfway between the present channel floor and the top of the nearly planar surface that sublacustrine erosion developed on exposures of unit B or C at the close of unit C deposition. It appears that the amounts of dissection prior to and following deposition of unit D were similar, and this implies that comparable climates and periods of time preceded and followed deposition of that unit.

In subsurface, the Overburden Mud (and thus unit D of this paper) averages about 7 m thick, but isopach contours of this subsurface unit (pl. 1) show a fairly systematically changing pattern of thicknesses. The criterion used here to determine the base of this unit in subsurface logs differs from that used earlier (Smith, 1979, p. 56, 66); here, only the core logs of Haines (1957, 1959) were used, as we know that the logging procedures were uniform. The contact between the Upper Salt and Overburden Mud is here placed at the top of the highest zone of mud-free salt that is several feet thick and clearly part of the Upper Salt. The resulting isopach contours on the Overburden Mud define a unit that ranges from less than 15 ft (4.6 m) thick to more than 40 ft (12.2 m) thick.

Within the present limits of Searles (dry) Lake, the thickest zones of the Overburden Mud are composed almost solely of mud; they overlie the outer rim of the subsurface Upper

Salt, whose lateral limits (Smith, 1979, fig. 27) are generally within a kilometer of the 40-ft isopach contour of the Overburden Mud (pl. 1). The thinnest zones overlie the north-central part of the Upper Salt. A complete isopach map of unit D (including the Overburden Mud) would show a circular zone just inside the edge of the present dry lake in which the unit has a thickness of more than 35 ft (11 m) and a thinning from all directions toward the center of the lake, where it is less than 20 ft (6 m) thick. Outside the limits of Searles Lake, unit D thins over a short distance to thicknesses less than 1 m.

Surface and subsurface evidence combine to show that unit D was deposited by an unusual lake: Its subsurface clastic deposits have a lower percentage of microcrystalline carbonate than any other perennial-lake unit (Smith, 1979, table 18); its saline layers are discontinuous and commonly composed of mixed aggregates of loose crystals (Smith and Haines, 1964, p. 34); and its basal contact beneath the present, nearly flat dry-lake surface has a concave-downward shape (pl. 1). These properties require development of a depositional model that differs substantially from those envisioned for earlier perennial lake stands. The most important element of this model is recognition of the evidence that expansion of the lake that deposited unit D followed the desiccation of the Upper Salt (Smith, 1979, p. 112). This means that fresh, rapidly moving water flowed directly onto the outer edges of the exposed salt, and those areas underwent the most intense solution. Presumably, less solution of salt occurred in the central area because by the time the inflowing water reached them, it was not flowing as rapidly and was partly or totally saturated with salts. This solution pattern meant that relative to the peripheral zone of deep solution, there was a shallower underwater plateau of undissolved salt, 20+ ft (6+ m) high, in the north-central part of the lake.

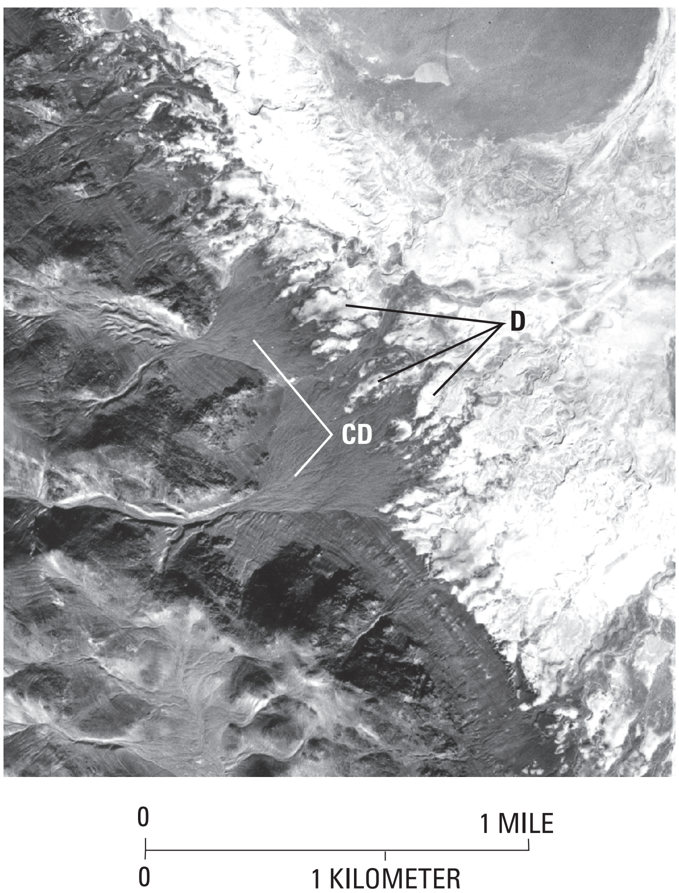


Figure 23. Vertical aerial view of two alluvial fans (left-center of photograph) at east end of Spangler Hills (pl. 4, secs. I19 and I30). North is toward top. Note lack of shorelines on the fans, composed chiefly of unit CD, even though they were later partially covered by lake that deposited unit D, whose silts and gravels overlie the coarse gravels of unit CD along the toe of the fans. Light-colored deposits northeast of fans are lacustrine sediments of units B, C, and D. (Segment of USGS photograph AXL-33K-117; because of the direction of the sun, this image is better seen in three dimensions when turned upside-down.)

The inflowing water came mostly from China Lake overflow via Salt Wells Valley (fig. 1*B*), which is why the deepest and widest zone in which salt was removed by solution was along the southwest edge of the exposed salt body. Smaller volumes of water from Valley Wells, Randsburg, and Teagle Washes are probably responsible for the less intense solution along the southern and and northern edges, and still smaller volumes from the Argus and Slate Range canyons produced even shallower peripheral zones of solution. As the clastic loads brought by the inflowing waters entered the new lake, they tended to fill the deeper zones around the edges rapidly, and the floor of the lake once again approached its equilibrium shape—that of a shallow basin. This selective solution pattern is considered responsible, therefore, for the concave-downward geometry of the basal contact of the Overburden Mud—the central facies of unit D of this report (pl. 1). Outside of the area of the Upper Salt, no solution occurred, and sediments deposited in this zone were only a meter or two thick.

Planimeter measurement of the areas of isopach contours (pl. 1) allows approximation of the volume of salt that was dissolved from the zone surrounding the underwater plateau (about $8x10^8$ m^3). Converting this volume to weight of salts ($17x10^{11}$ kg), and using the estimated volume of water in a 60-m-deep lake ($16x10^9$ m^3; Smith, 1979, fig. 32), suggests that the salinity was near 110 g/L. If some salt was dissolved from layers above the preserved level of the underwater plateau, the lake's salinity was higher, but saturation was unlikely. Smith and others (1987, p. 814-817) describe processes observed in 1969-70 at Owens Lake, California, when fresh water flowed onto the 2-m-thick salt body. They found that a year later only about 20 percent of the salt had dissolved at the study area, which was 12 km south of the inflow source, and the lake water, at 135 g/L, had only half the salinity required for saturation. It was later found that a thin layer of sediment had been deposited on the submerged surface of the partially dissolved salt, effectively armoring it. That layer apparently halted solution of the Owens Lake salts long before the lake water became saturated. This process seems likely to be one that could accompany the solution of exposed salts in any lake.

Partially dissolved halite crystals in subsurface samples from this unit also show that the lake water that reworked them was unsaturated (Smith and Haines, 1964, p. 16), but the majority of crystals are now euhedral, requiring a post-depositional history of overgrowths. Therefore, the impure, poorly consolidated aggregates of salt crystals in the Overburden Mud (or unit D) are viewed as reworked mixtures of new clastic-silicate material and older salt crystals that were transported as sediments after being disaggregated during partial solution of the outer facies of the Upper Salt body. These impure aggregates of salt crystals and mud are concentrated in the central facies of the deposit. This may be because most salts have lower densities than silicates. The density of quartz is only about 23 percent more than halite, but after subtracting the buoyancy of these minerals in a brine having a density of 1.1, quartz is 46 percent heavier than halite. Salt crystals, therefore, may have responded to sorting processes like silicate fragments half their size, and thus they were transported and concentrated in the more central and deeper parts of the water body.

Tufa

Tufa deposits that take the form of encrustations, mounds, terraces, and pinnacles locally provide the most scenic and unusual aspect of the Searles Lake Formation. The tufa is composed of porous calcite or aragonite that is light to moderate brown (5-10YR4-6/2-4) on weathered surfaces and very pale orange to light brown (5-10YR6-8/2-4) where unweathered. Tufa assigned to this formation is found in mappable amounts at all elevations between the 1,680-ft contour and the top shoreline at 2,280 ft, but the most notable concentrations are found between the 1,800-ft and 2,000-ft contours and along the top shoreline. Concentrations of tufa large enough or thick enough to map are limited to the north, west, and south sides of Searles Valley (cover image and pl. 1). The reduced amount of tufa along the east side of Searles Valley is attributed to the probable continuous wave action along that shore, a result of the prevailing winds out of the west. This inference appears to conflict with some of the conclusions reached in a later section based on the directions in which lacustrine bars were built when the lake was nearly full, but those reconstructed wind directions reflect the most intense storms

Figure 24. Scattered fragments that represent the characteristic appearance of the gravel and sand facies of unit D where it extends onto the flat surface of Searles Lake (pl. 1). The fragments are considered to be remnants of a more continuous layer that was introduced near the close of unit D time and spread laterally by lake-current action. Hammer is 33 cm long. View toward southwest; location: plate 1, sec. C34-f.

rather than directions that prevailed during the long periods between storms.

In this paper, tufa deposited as part of the Searles Lake Formation is described as being one of two types, although none of the geologic maps (pls. 1-4) differentiate between them. The older form is termed lithoid tufa (Gr., *lithoeides*, like a stone), an allusion to its more dense and massive appearance; the term was proposed by Russell (1889, p. 311) for application to tufas observed at Mono and Lahontan Lakes. The younger form is termed nodose tufa (L., *nodosus*, knot), alluding to its node-covered outer surface. The term was first used to describe tufa, I believe, by Scholl (1960, p. 419).

Scholl (1960, p. 416-418) divided the tufa lithologies found in the south half of Searles Valley into seven types: "massive lithoid" tufa constitutes the older tufa unit of this report and was discussed earlier. His "stony lithoid" and "cavernous lithoid" tufas are combined in this study into "lithoid" tufa. His "dendritic," "nodose," "tubular," and "lobate" tufas are combined here into "nodose" tufa. Lithoid tufa is most commonly found in unit A of the Searles Lake Formation, but a few similar tufa beds are found in unit AB. Nodose tufa growth took place mostly during deposition of units B, BC(?), and C, although instances were noted where this tufa type is also interbedded in sediments of unit AB. Tufa is not associated with units CD and D.

Lithoid tufa is the most abundant type of tufa in Searles Valley, and the most unusual form of lithoid tufa is as tufa towers. The Pinnacles (secs. I32, I33, L4, and L5, pl. 4), near the center of an area designated as The Trona Pinnacles National Natural Landmark because of them, are tufa towers that are as tall as 25 m but more commonly are about half that high (figs. 25 and 26). Nodose tufa as thick as 1 m coats many of these towers, but the locations, shapes, and sizes of The Pinnacles were determined by the earlier episode of lithoid tufa growth. Similar but smaller towers composed mostly of lithoid tufa once characterized much of the southwest arm of Searles Valley, but mining of them in the 1950s and 1960s for ornamental rock has destroyed most. The lithoid tufa towers now project up through all younger deposits, but stratigraphic evidence indicates that many of the towers began to form early during deposition of unit A. Subunit sa3 commonly has tufa towers or tabular layers at its base; examples are found at elevations of 1,720 ft (sec. I32-r, pl. 4), 1,760 ft (sec. I32-m), 1,920 ft (sec. K13-r, K24-p), and 1,960 ft (sec. L7-q). The bases of many of the large lithoid tufa towers and tabular masses, however, are concealed, and they could have commenced their growth on strata near the bases of subunits sa1 or sa2; examples where this relation is exposed are found in secs. L8-h and L18-c (pl. 4), where tufa is mapped resting on gravels of the Christmas Canyon Formation (fig. 9).

Massive tabular deposits of lithoid tufa also are found associated with the highest shoreline at 2,280 ft and between the 1,800-ft and 2,000-ft contours along the Argus Range and Spangler Hills. In sec. H11-l (pl. 1), lithoid tufa forms a bench 300 m long and 3 to 10 m wide along the highest shoreline, and its deposits extend 15 m down the slope. In sec. K22-e,f (pl. 1), at and below the highest shoreline, lithoid tufa forms a discontinuous sheet 0.3 to 2.0 m thick that covers an area of about 0.3 km^2 southeast of the shoreline. Smaller tabular masses of lithoid tufa are found at and below 2,280 ft elevation in almost every canyon in the Argus Range and Spangler Hills.

These tufa deposits are considered to be the combined product of inorganic and organic reactions. The organic processes inferred here depend on the consumption of CO_2 by algae. Very similar structures growing on the floor of Lake Van, Turkey, that have similar mineralogies, zonations, and textures, are shown to be in large part the products of microbes (Kempe and others, 1991), but microscopic textures show algae that require sunlight to have been involved in the formation of the Searles Valley tufas. Inorganic chemical reactions that could have contributed to the deposition of tufa are as follows:

$$CO_2 + H_2O = H_2CO_3 \quad (1)$$

$$H_2CO_3 = H^+ + HCO_3^- \quad (2)$$

$$HCO_3^- = H^+ + CO_3^= \quad (3)$$

$$Ca^{++} + HCO_3^- + OH^- = CaCO_3 + H_2O \quad (4)$$

$$Ca^{++} + 2\,HCO_3^- = CaCO_3 + H_2O + CO_2 \quad (5)$$

$$Ca^{++} + CO_3^= = CaCO_3 \quad (6)$$

Because H^+ appears on the right sides of equations (2) and (3), and OH^- appears on the left side of equation (4), these reactions are affected by pH change. Mixing near-neutral spring waters that contain significant amounts of Ca^{++}, H_2CO_3, and HCO_3^- with alkaline lake waters that contain abundant $CO_3^=$ and a greater concentration of OH^- than of H^+ drives all of the above equations to the right. This promotes increased concentrations of $CO_3^=$ and, to the extent that Ca^{++} becomes available, precipitation of $CaCO_3$ (equations 4, 5, and 6). Similarly, loss of H_2O by evaporation (equation 4), or loss of CO_2 if its partial pressure exceeds that of the atmosphere (equation 5), promotes precipitation of $CaCO_3$.

Two inorganic processes appear to have been active, most prominently in the deposition of the lithoid variety of tufa: (1) Springs on the floor of the lake injected relatively fresh, Ca-bearing ground water into the relatively saline, high-pH, CO_3-rich lake, causing precipitation of $CaCO_3$ around the orifice; this process primarily followed equation 6, but processes following equations 4 and 5 probably also contributed. These precipitates grew into pinnacle-shaped masses that contained internal vertical conduits, still preserved in many of the tufa towers, which allowed spring-water injection to continue. Many of the pinnacle-shaped tufa masses are crudely aligned in en echelon patterns (figs. 25 and 26; pl. 4), as if the distribution of springs that produced them was controlled by a series of similarly oriented faults. A classic discussion of this process, based on evidence observed around Mono Lake, is provided by Russell (1889, p. 310-315). (2) In alkaline saline lakes, the partial pressure of CO_2 in the lake water can be much greater than that of the CO_2 in the atmosphere (Smith and others, 1987, p. 824). For this reason, the splashing of such waters along shorelines increases the water's surface-exchange area and causes loss of CO_2 to the atmosphere, producing $CaCO_3$ (equation 5). Additional Ca^{++} can also come from surface drainage, increasing the volume of calcite and aragonite near the point where the drainage entered the lake (equation 6). This process is considered primarily responsible for the persistent tufa benches that parallel contour lines in many parts of the basin.

Algae may not have been required for deposition of the lithoid tufa that formed the pinnacle-shaped and shoreline-bench masses, but remains of algae or organically pigmented zones are found in all samples of these materials. It appears that algae took advantage of the favorable environment provided by the growing tufa structures. The tufa deposits supplied a firm substrate, and the crystallization of tufa, following equation 5, created excess CO_2 that was required by the algae during their photosynthesizing stage. Reactions in the wave-zone environment depleted some of the lake-water CO_2, but the shallow waters that characterized this zone also allowed ample sunlight, which was necessary for algal development. In this environment, loss of CO_2, as a result of algal consumption or escape to the atmosphere, thus drove equation 5 to the right and caused deposition of $CaCO_3$.

Nodose tufa deposits show more evidence of algal participation in their formation. They are darker brown (5YR3-5/2) than lithoid tufa because they contain more organic pigmentation, they tend to be thickest on the horizontal part of the substrate surface that faces the sun, and their nodular surfaces parallel the remains of algae growth patterns as seen in thin section (discussed below). Possibly the greater amount of organic pigmentation is a result of the younger age of these nodose deposits, relative to the age of the lithoid tufa, but the mineralogic and internal and external morphologic differences between the two types of tufa suggest that they are products of a different balance between depositional processes. Details of the role of modern algae in this depositional process, based on evidence observed in and around Mono Lake, California, are described by Scholl and Taft (1964).

Megascopic study of lithoid tufa samples reveals many different textures. The most common is a crude lattice struc-

Figure 25. Oblique aerial view, looking north-northwest, of The Pinnacles and surrounding areas. Dirt road (light, irregular line leading toward base of photograph) indicates scale. Teagle Wash, trending diagonally toward upper right, divides pinnacle clusters. Tallest pinnacle (circled, right of center) is more than 30 m high. Straight feature in upper left is track embankment and cut of Trona Railway. Prominent gravel bar (dark ridge) between most distant pinnacles and railroad is The Pinnacles bar; gravel (subunit sa4) was derived from east end of Spangler Hills (upper left corner of picture).

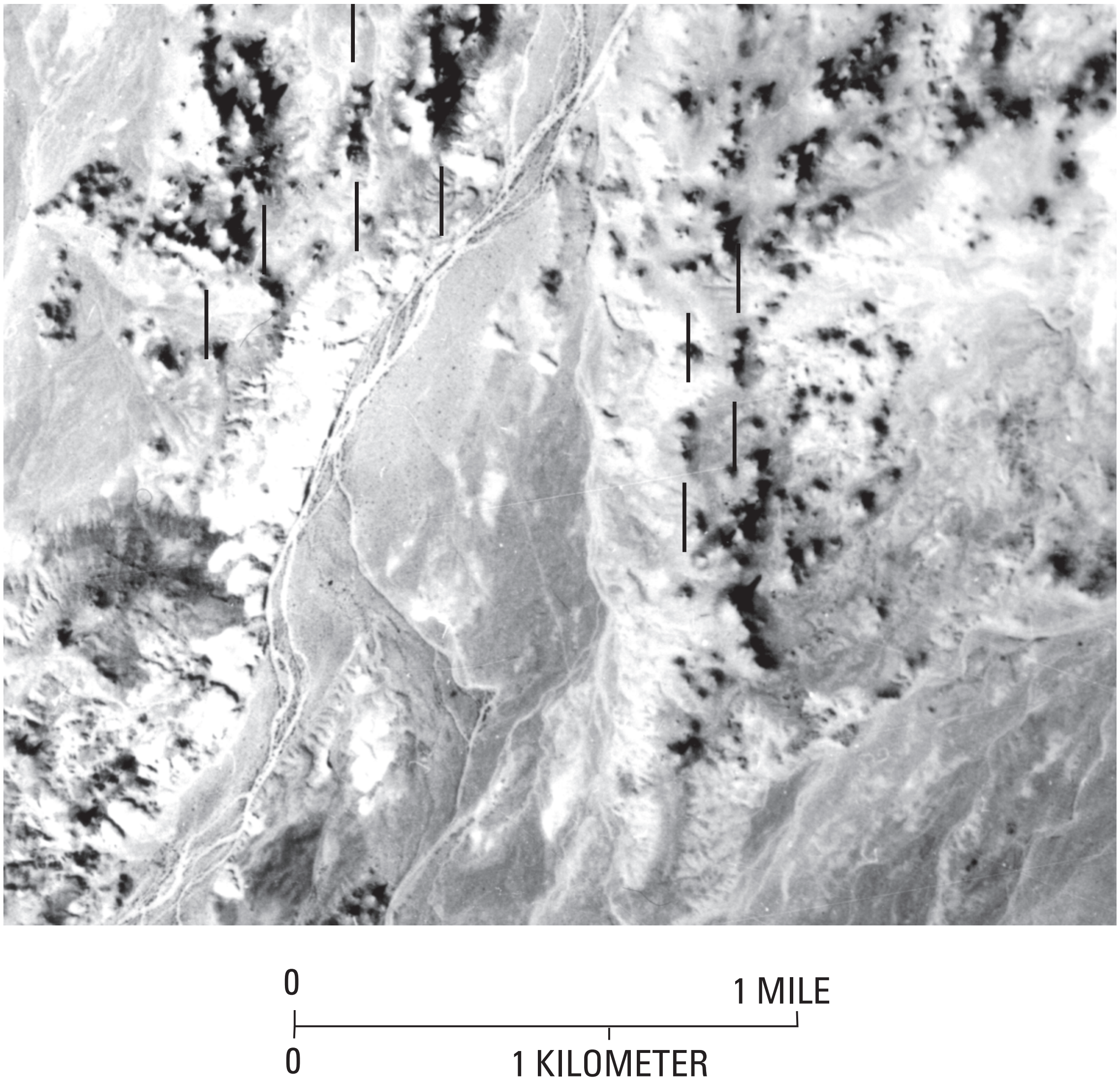


Figure 26. Vertical air photograph of The Pinnacles and surrounding area; north is toward top. Note the tendency for groups of pinnacles to form north-trending rows (marked by long dashes), interpreted to be a result of the alignment of sublacustrine springs along fissures. The lacustrine bar and railroad, noted in figure 25, are also visible in this view. (U.S. Navy photograph PTK-5-023.)

ture composed of short indistinct vertical and horizontal components about 10 to 20 cm in length (fig. 27*A*; see also Scholl, 1960, fig. 3b), but outcrops were studied that displayed four or five different textures within a 1- to 2-m^2 area. All, however, had large amounts of void space, and hand-lens study revealed botryoidal calcite linings on these surfaces in most samples. Scholl (1960, p. 418) reports the bulk density of lithoid tufa to average 1.3, meaning that approximately half the volume of an average sample is void space. X-ray diffraction analysis indicated all lithoid tufa samples to be calcite.

Thin sections of lithoid tufa reveal structures much like those illustrated by Scholl (1960, fig. 4). The material considered to be primary is cryptocrystalline calcite that in plane polarized light is tinted by its organic content to varying intensities of yellow brown (10YR5-6/2-4). All samples include areas characterized by banded structures created by differing concentrations of brown pigment considered to be algal remains. The crudely circular or elongated structures, typically 0.2 mm in the shortest dimension, tend to be massive in the middle and banded in their outer layers. In some lithoid tufa samples, though, 30 to 90 percent of the calcite is secondary in the form of discrete crystals 0.1 to 0.2 mm long. Some of these crystals are cross-cut by pigmented zones that parallel the outer boundary of the underlying more heavily pigmented, cryptocrystalline algal structure. As recrystallization processes normally reject material not required for the new crystals, it appears that the larger crystals were produced by inorganic crystallization of calcite. Later, though, algal mats temporar-

Figure 27. Outcrop and thin-section photographs of tufa. *A*, Vertical face of a lithoid tufa outcrop. Irregular lattice-like texture is characteristic of this unit, but many other varieties also are noted. Scale is 15 cm long. *B*, Outcrop of nodose tufa. Nodular surface is caused by large numbers of hemispherical algal growth sites that collectively form a cauliflower-like outer surface. Pen cap is about 6 cm long. *C*, Thin section of nodose tufa in plane-polarized light. Photograph by D.W. Scholl, who states (1960, fig. 5) that "[d]ark-colored lobate layers of banded tufa are probably algae secreted; banded calcite laths radiating from these layers may be largely of inorganic origin. Conceivably, the layers represent annual accruements. The oval pigmented bodies near the center of the photograph may be algal cells." Image is about 4.7 mm wide.

ily were re-established on the outer surface of the recrystallized material, and the new calcite deposits (containing algal remains) adopted the crystallographic orientation of the inorganic substrate. In more definite examples of secondary crystallization, radial wedges or anhedral crystals of colorless, optically continuous calcite cross-cut and replaced large sections of the cryptocrystalline material, sometimes systematically excluding the calcite in the center of the algal structures and sometimes including it. Angular silicate fragments are seen embedded in the cryptocrystalline calcite of many samples.

The other type of tufa in Searles Valley is nodose tufa. This is most commonly found as layers resting on lithoid tufa, bedrock, or lacustrine sediments. Deposits 2 to 5 cm thick are present over the same elevation range as lithoid tufa, and masses 50 to 100 cm thick are found in some areas between the 1,720-ft and 1,880-ft contours. Beds of nodose tufa, 2 to 4 cm thick, also occur within units AB, B, BC, and C of the Searles Lake Formation.

Hand specimens of nodose tufa are mostly characterized by small-scale cauliflowerlike forms, with upward-flaring clusters of lobate masses that are 0.5 to 1 cm in diameter at their widest point (fig. 27B). The lobes are composed of adjoining hemispherical, tubular, or crenulated structures a few millimeters in diameter that are believed to be individual algal colonies (Scholl, 1960, figs. 4-6). Weathered surfaces are commonly pale brown (5YR5/2); fresh surfaces are lighter. Spaces between clusters generally range from 2 to 5 mm at their bases to less that 1 mm at their tops; lacustrine silt or sand fills these spaces.

Thin-section study of nodose tufa samples confirms the cauliflowerlike description and shows the algal structures to be lobate bands that parallel the outer surfaces. The material is composed of cryptocrystalline aragonite that is tinted with varying intensities of brownish pigmentation. Individual algal structures are mostly 1 to 3 mm in diameter in a horizontal plane, but vertically oriented sections reveal lobate growth patterns having wavelengths of 10-20 mm (fig. 27*C*). Some zones of larger carbonate crystals appear to be secondary, but as in the lithoid tufa samples described earlier, a few pigmentation bands within these larger crystals suggest that there were temporary resumptions of organic tufa generation after the period of secondary calcite crystallization had started.

Both thin-section and hand-lens observations show secondary botryoidal calcite or aragonite linings in the cavities of many nodose tufa samples. Samples of tufa submitted for ^{14}C dating early in this investigation yielded dates that were much too young according to stratigraphic evidence. More careful study of samples showed that contamination with more recent carbon in the form of secondary carbonate is common among the porous varieties of tufa. This inference was subsequently confirmed by Benson (1978, p. 303-312) in his study of tufa samples from Lake Lahontan, Nevada. He concluded that dates from dense tufa were the most reliable because they were nearly identical to dates from gastropods in the same sample.

Undifferentiated Gravels

In a number of places in Searles Valley, alluvial gravels that were thought to be equivalent in age to some part of the Searles Lake Formation could not be traced satisfactorily into any one unit. They have been assigned to the undifferentiated gravels unit (sg), which is considered the stratigraphic equivalent of the entire formation. Most of these gravels crop out at levels above 2,280 ft where lacustrine deposits are missing, or are gravels below that elevation that are isolated and cannot be traced laterally into lacustrine sections.

Gravel deposits assigned to this unit are considered to be of an age equivalent to the Searles Lake Formation because they are not graded to the levels of the middle and late Holocene alluvial units, nor are they similar to the lithologies of, or to the soils developed on, the Christmas Canyon Formation and equivalent or older alluvial units. Many of these gravel deposits are coated with desert varnish that creates a dark brownish-orange hue, similar to the outcrop colors of the alluvial layers in units A, AB, and BC of the Searles Lake Formation, but color alone was not considered a satisfactory basis for assigning the gravels to any one of those units.

Middle and Late Holocene Units

Five sedimentary units that are younger than the Searles Lake Formation have been separated on plates 1 through 4. The older alluvium unit appears to be a product of a depositional regime and climate that no longer exist. The windblown sand and colluvium and the windblown dune sand units are still accumulating or undergoing modification, but the major volumes of these units appear to have been deposited under aeolian regimes that are extinct. Sediments mapped as playa silt and active alluvium continue to accumulate.

Older Alluvium

Inactive alluvial deposits assigned here to the older alluvium unit (oal) account for more than three-fourths of the areas that would ordinarily be mapped as “alluvial” fans. (Observations in other parts of the southeastern California deserts suggest that the ratios between areas covered by inactive alluvium of the type represented by this unit and truly active alluvium are similar to these ratios in Searles Valley.) Deposits of older alluvium typically have a slightly undulating, unchanneled surface, with small accumulations of windblown sand around the bases of plants, and a weak lag gravel in areas where the parent material contains pebbles (fig. 28). Surface relief is almost always only a few centimeters, and bar-and-swale topography is absent. Colors range from near grayish orange (10YR7/4) in areas draining granitic terrane to light olive gray (5Y6/1) or near-gray hues in areas draining terranes of darker rock types. Beneath the surface, small pebbles constitute a few percent of the deposit, and sediment colors are a little darker and more intense. In most areas, the older alluvium unit is less than 1 m thick, and in areas where it has been dissected by channels transporting active alluvium, the channel depth is most commonly between 0.3 and 0.6 m. Obsidian flakes and other Native American artifacts are present on the surface of this unit, suggesting that these deposits have not been reworked during the past century.

It appears that these sediments were deposited by ordinary alluvial processes during a climatic regime that led to alluviation over much of the valley floor yet did not produce torrential flood events. Large fragments are rare in these sediments, unit thickness is fairly uniform, and channeling at the base of the unit generally created relief that is no greater than 10 to 30 cm. Although channels must have originally characterized this surface, the presently smooth surfaces appear to be the result of enough time to allow reworking of the top layers by small animals, wind, and rain that induced microerosion. The rain apparently percolated down into the deposit without developing channels. The surfaces of older alluvium accumulations resemble those attributed to sheetwash depositional mechanisms, but this depositional mechanism is believed not to be involved. Sheetflood bedforms, like those described by Wells and Dohrenwend (1985, p. 512-514) from piedmonts in nearby desert areas, are not found on any of these surfaces.

Around the edges of Searles Lake, sediments assigned to the older alluvium unit overlie all facies of unit D of the Searles Lake Formation, although the base of the unit in some areas could have been contemporaneous with deposits of unit D. Because the ^{14}C age of the middle of the Overburden Mud in subsurface, the equivalent of unit D, is about 3,500 years, the base of the older alluvium unit, if not partly contemporaneous with unit D, seems likely to have an age in the range of 500 to 2,000 years. Artifacts lying on its surfaces allow its younger age limit to be almost anything up to about A.D.1900, as a small population of Native Americans still lived in Searles Valley when it was first populated by miners and prospectors in the 1860s.

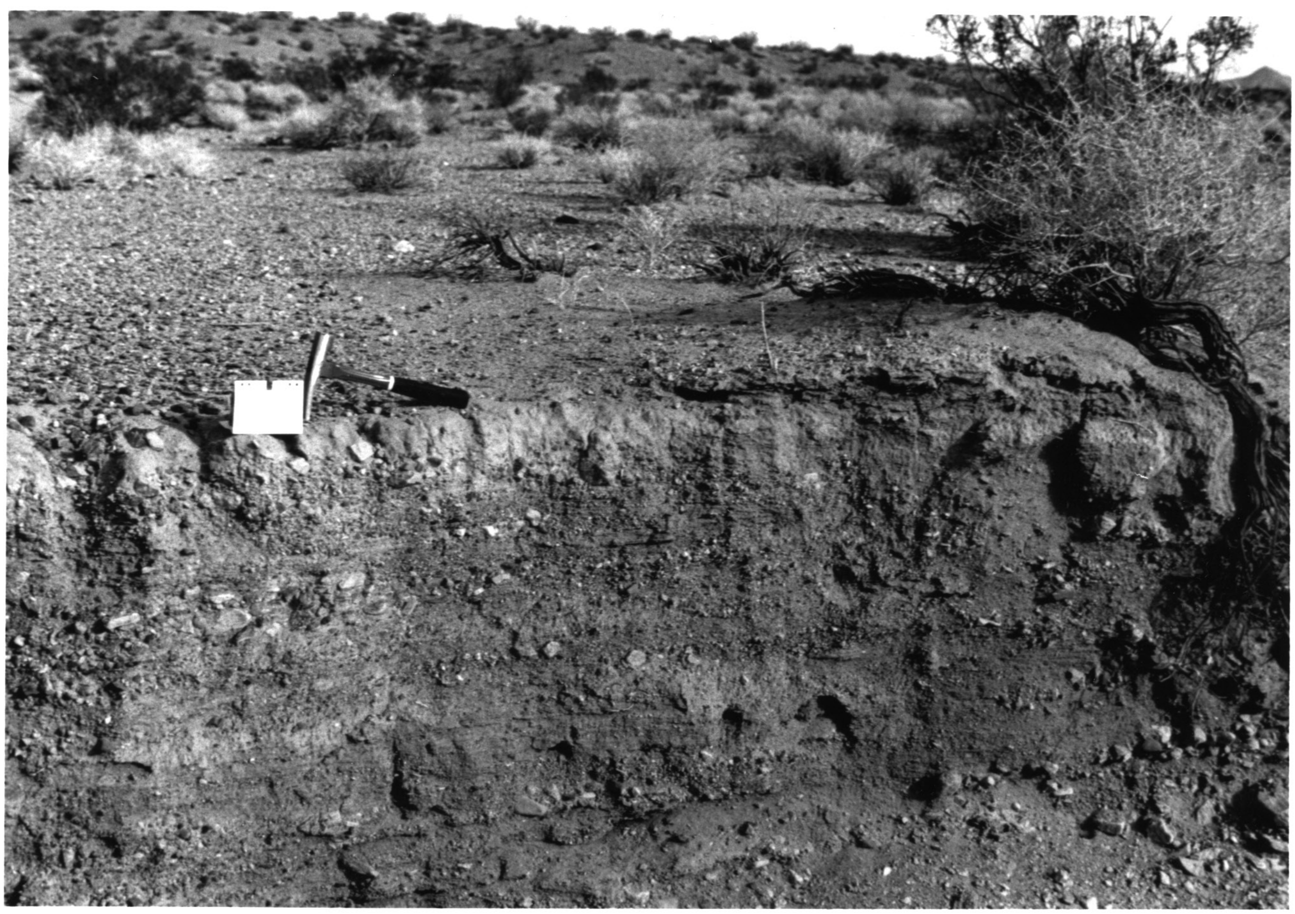


Figure 28. Characteristic lithology and unchanneled upper surface of older alluvium unit, exposed in modern stream channel. The sediment is fairly well bedded, but individual beds of granule- and pebble-size clasts rarely can be traced more than 1 m. Sorting is poor, but clasts larger than about 5 cm are rare. Note weak lag gravel and lack of channels on upper surface. Hammer handle is 33 cm long.

This unit is probably equivalent to the Post-Palmdale I deposits of Ponti (1985, p. 84) in the southwestern Mojave Desert. His Upper Palmdale unit has a stratigraphic position (his fig. 3) that is compatible with the older alluvium of this study, and it forms similar surfaces (his fig. 2), but the thickness and soil development of his Upper Palmdale unit are much greater (Ponti, 1985, p. 83) than found in these older alluvium deposits.

Playa Silt and Clay

Several small playa lakes have been formed in Searles Valley and adjacent areas where closed depressions have been created by lacustrine bars (K24-j and L18-p, pl. 4) or structural deformation (A9-b, L26-m, and M33-b). The playa surfaces are smooth and composed of silt or clay (unit ps) that is in most places well compacted though pervaded by desiccation cracks. Typical colors are grayish orange (10YR7/2). After exceptionally severe rainstorms, water runs into the playa lakes and stands on the surface for a short period. Small amounts of new sediment are deposited at those times, meaning that the surfaces of these playas represent areas of continuing accumulation.

Windblown Sand and Colluvium

Large areas that are covered by a mixture of aeolian sand and gravel are mapped as windblown sand and colluvium (unit ws). The largest of these areas are north, east, and south of Searles Lake, the surface of which was the main source of sand. Some sand, however, was derived also from erosion of fault gouge in the Slate Range—after being water-transported westward into Searles Valley, some of this sand was blown back toward the base of the range and part way up its flanks (Smith and others, 1968, p. 15). West of the southern Argus Range, deposits included in this unit form a sheet that nearly buries a low pass in the range. Severe modern windstorms rework the sand on the surface of these deposits, but the major part of this unit, which is a meter or two thick in most areas, was probably deposited at an earlier time. The colluvial aspect of these sediments consists of a percent or less of scattered pebbles, a few centimeters in diameter, that are distributed throughout the deposit. They appear to have been reworked from underlying alluvial units by burrowing animals.

These sediments are composed mostly of sand in the same size range found in the windblown dune sand unit, but the windblown sand and colluvium unit is in the form of sheets with no residual dune forms. Sediment colors are similar to those of the older alluvium unit, but distinguishing this unit from the others is easy because some areas within it are typically so filled with animal burrows that walking across it becomes treacherous and driving is nearly impossible. The windblown sand and colluvium unit rests on deposits of older alluvium and yet appears to be prehistoric; it could have been deposited during a period that was as long as 2,000 years or as short as a few centuries.

Windblown Dune Sand

Sand dunes (unit wd) ranging in height from 1 m to about 3 m rest on older deposits in a large canyon on the west side of the Argus Range at the latitude of Trona, and in small areas north, east, and south of Searles Lake. Colors typically are very pale orange (10YR8/2). Dune shapes are not symmetrical. Most dunes lie within areas mapped as windblown sand and colluvium, and they probably should be considered a still-active part of those larger deposits. These dunes are most generally free of vegetation, and modern windstorms constantly modify their shapes and destroy vehicle tracks.

Active Alluvium

Alluvium in all modern, normally dry washes in Searles Valley and adjacent areas is reworked and transported downstream every few years. Storms in the area, which can occur in any season but tend to be most intense in autumn and winter, are sometimes so localized that the most voluminous streamflow events occur in only a small area—sometimes in a single canyon.

The composition of active alluvium depends on the lithology of the bedrock and older sediments upstream from a given site. Most alluvium (unit al) is fine to coarse sand, and the larger fragments generally constitute 5 to 25 percent of the sediment. Fragments 0.2 to 0.5 m across are common in many washes, and boulders measuring several meters in the long dimension are found in the alluvial floors of a few washes leading from the Slate and Argus Ranges. Colors of the sand matrix vary, but most center around grayish orange (10YR7/2).

Sediment firmness, an important factor when driving in active alluvial washes, varies greatly from year to year, apparently as a result of the character of the last significant streamflow event. Factors that may help determine these characteristics include (1) the volume and velocity of water flowing during an event, which determines the thickness of the alluvial bed that is remobilized, and (2) the rapidity with which alluvial transport processes ceased. The latter factor determines whether the alluvial sediment becomes close-packed and firm as a result of winnowing during a gradual decrease, or whether the transported fragments are released from suspension so rapidly that winnowing and sorting cannot occur, leaving the deposit uncompacted and soft.

Geomorphology

The very prominent shorelines around the edge of Searles Valley first alerted geologists to the former existence of a large lake in this basin. Shorelines are preserved at many levels, but the highest, at about 2,280 ft, is by far the most prominent. This resulted from the stabilizing effect of the spillway that maintained the water surface at this level, allowing erosional and nearshore depositional processes to persist for long periods. Whenever the lake surface fell below spillway level, seasonal and longer term climatic fluctuations would have caused the lake level to migrate up and down and rarely occupy any one level for comparably long periods.

Shorelines are nearly irrefutable evidence of a former lake in a basin. However, they provide little information on the number, history, or ages of the one or more lakes that formed them. In Searles Valley, where many details of lake history can be derived from the subsurface and exposed stratigraphy, it is evident how complex such a history can be, yet the most careful study of these shorelines could not have produced the detailed information that has been derived from this stratigraphic study.

Shorelines around Searles Valley (or any valley that once contained a large water body) are of two types, erosional and depositional, and the volumes of rock removed by erosion in some areas must be roughly balanced by the volumes of sand and gravel deposited in the nearshore zones of other areas, minus the volume of sediments brought in by streams. Erosional shorelines in Searles Valley are best developed along the east side of the valley on the flanks of the Slate Range and along parts of the south edge of the valley. The Slate Range has undergone extensive tectonic brecciation, and shoreline erosion easily removed large amounts of bedrock from exposed ridges that projected into the lake. Longshore currents transported the fragments to more protected areas within nearby canyons or to other parts of the valley. Along the flanks of the Slate Range, bedrock erosional benches as wide as 100 m are found at the level of the highest lake. Thick sections of strongly indurated older gravel were also eroded by waves, leaving shoreline scarps at the 2,280-ft level that are 3 m to more than 10 m high in places. If the original slope of the older gravels surface was 5°, a 10-m scarp implies more than 100 m of horizontal retreat of the wave-cut cliff. The highest shoreline level was reoccupied more than once during deposition of the Searles Lake Formation, each episode presumably contributing to the erosional process. Searles Lake history as reconstructed later in this paper (figs. 39 and 40) shows that the lakes with maximum depths accounted for about 18,000 years of the 150,000-yr period; 100 m of shoreline retreat during this length of time would translate into a horizontal erosion rate of 5.6 m/k.y.

Study of the areas characterized by swarms of erosional shorelines that were mapped as deposits of units A, B, or C of the Searles Lake Formation, as explained in the description of unit A, reveals that each shoreline is visible in part because of the changes in slope above and below the knickline (the base of the eroded slope), but more importantly because of variations in the lag gravel sizes that reflect horizontal zones where wave energy was greatest and least. The changes in slope are commonly very slight, and many might not be recognized while traversing the area. Recognition of shorelines from a distance or on aerial photographs, however, is easier because the concentrations of smaller fragments in the area below the knickline have led to concentrations of windblown fine sand and silt in their matrix. Plants favor these levels because they retain more moisture, and horizontal concentrations of plants on a gentle slope can make such shorelines highly visible.

Depositional shorelines, more commonly described as beaches or horizontal concentrations of shallow-water tufa, are also abundant around the edges of Searles Valley. Surfaces of these deposits have more varied slopes than do the erosional shorelines, and when viewed in low-angle sunlight, they provide highly convincing evidence of a former lake (fig. 29). As noted previously, the beaches tend to be composed of clasts that are characteristically smaller in successively younger deposits occupying the same general area. This statement can be best documented where the gravels of each unit can be traced downhill into their deeper water stratigraphic equivalents, which can be placed with confidence into stratigraphic context. In many regions, the sediment layer forming depositional shorelines is less than 1 m thick because it formed only a veneer along the edges of the successive lakes. Because of this, relatively minor erosion over large areas has removed one or more of the younger gravel layers, allowing underlying sediments that constituted older beaches and nearshore bars to be exposed and mapped.

Tufa deposits in the form of benches define shorelines in many areas. The most massive benches are the deposits along and immediately below the highest shoreline in the Argus Range and Spangler Hills. The most extensive tufa platforms along these shorelines were described in the section on tufa deposits of the Searles Lake Formation. Much smaller concentrations of tufa also occur as benches and horizontal rows at the same and many lower levels, including areas on the preserved remnants of the Searles Lake Formation west of the Slate Range (fig. 30), where they are too thin to map separately from the underlying deposits of unit B or C with which they are generally associated.

Offshore bars in lakes commonly lie some distance from the shore. Most of the lacustrine bars in Searles Valley would be classified as bayhead bars, baymouth bars, or spits. Transport directions are determined from clast composition. At least 19 distinct offshore bars can be identified, and many of them have multiple subordinate crests at slightly different levels. When their crest lines are mapped, most are in the form of smooth curves (fig. 31) that reflect wave refraction and current patterns in the lake but not minor changes in the topography of the lake floor. Elevations of offshore bar crests, therefore, may vary over a kilometer or more by more than 10 m, and they clearly were not deposited along the shore or at uniform distances from shore.

In cross section, most lacustrine bars in Searles Valley are asymmetrical. Upslope faces can be as steep as 25°; downslope faces are more commonly 1° to 5°. Where bars have been dissected, internal bedding near the surface normally has dips similar to the preserved surface slopes, although cross-bedding within individual beds generally dips at angles near 30°. Some dissected bars show that the crest migrated upslope as the bar accumulated; this is especially well displayed in exposures of the internal structure of the bar composed of unit A gravels immediately northwest of The

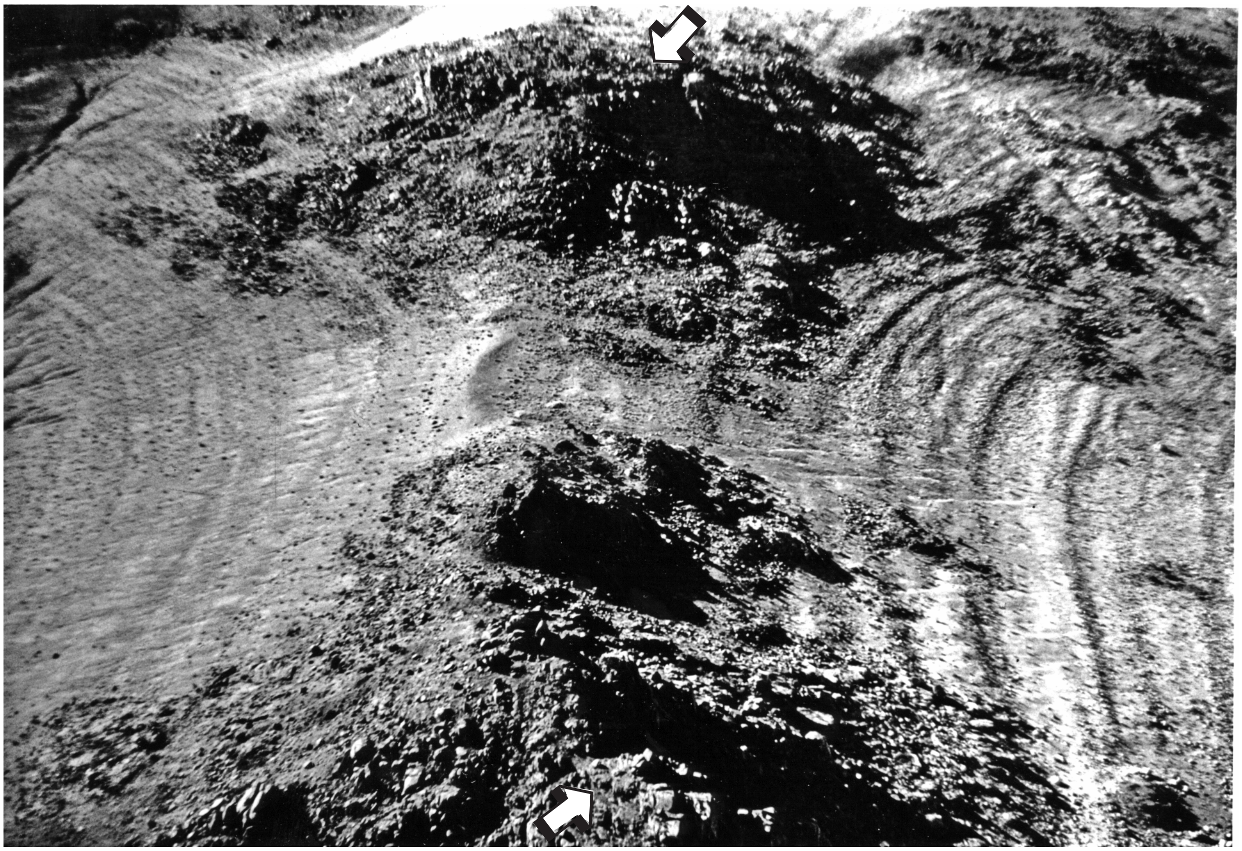


Figure 29. Depositional shorelines, mostly beach deposits in this example, provide unambiguous evidence of former lakes. Most of the deposits to left of crest (which formed a tombolo during its deposition) are composed of unit B, deposits to the right are mostly unit A. Distance between arrows is about 400 m.

Pinnacles. Other good exposures of the internal structures of bars are found in secs. C3-r and C15-q (pl. 2*A*), H21-r (pl. 3*B*), and M18-g,k (pl. 2*B*).

Sediments constituting offshore lacustrine bars range from cobbles as large as 15 cm in their longest dimensions to very coarse sand. Rounding also varies—some deposits are characterized by a high percentage of subangular fragments, whereas others are composed of notably well rounded fragments. Some gravel bars have a bimodal distribution of their clast sizes; sediment-size analyses of these materials (appendix 2) show that while most bar gravels contain little medium to coarse sand, 10 to 15 percent contain fine to very fine sand plus silt and clay. The gravel beds, nevertheless, appear clast-supported; that is, most large fragments are in contact with each other and otherwise separated by voids except where calcite cement or wind- or water-transported fine sediment has filled the voids.

The two shallow tufa-lined canyons whose origins are inferred to have been the cause of V-shaped channels cut in subunit sab6 (discussed earlier) are bounded by levees of coarse rubble as high as 2 m (fig. 20*B*). The rubble fragments are angular and 0.2 to 1 m across. Bedrock was not significantly eroded, but the desert varnish coating on bedrock was removed during sediment transport and has not been entirely restored. The slope angles of the bedrock segment of the channel range from 13° to 20°. The water required to mobilize and transport debris of the size and volume found in these levees must have been derived from an approximately 0.02-km^2 precipitation-collection area above the highest elevation of the levees (about 2,240 ft). Possibly at that time, when subsurface mineralogic evidence for subsurface-equivalent unit S-7 of the Lower Salt suggests cooler climates than at any other period (Smith, 1979, p. 89-90), a large volume of snow accumulated as drifts on the east (presently, the lee) side of the Spangler Hills. An intense, warm rain could have later mobilized this snow mass very rapidly, creating a slurry of snow-water, older lake sediments, and talus that had the competency to carry rocks of the sizes found in the levees of these two channels.

At the other end of the erosion-intensity spectrum is the widespread evidence of exhumation of fairly large surfaces that were previously buried by younger lacustrine deposits. This process must have required a very uniform erosional removal of the overlying layers composed of soft deposits such

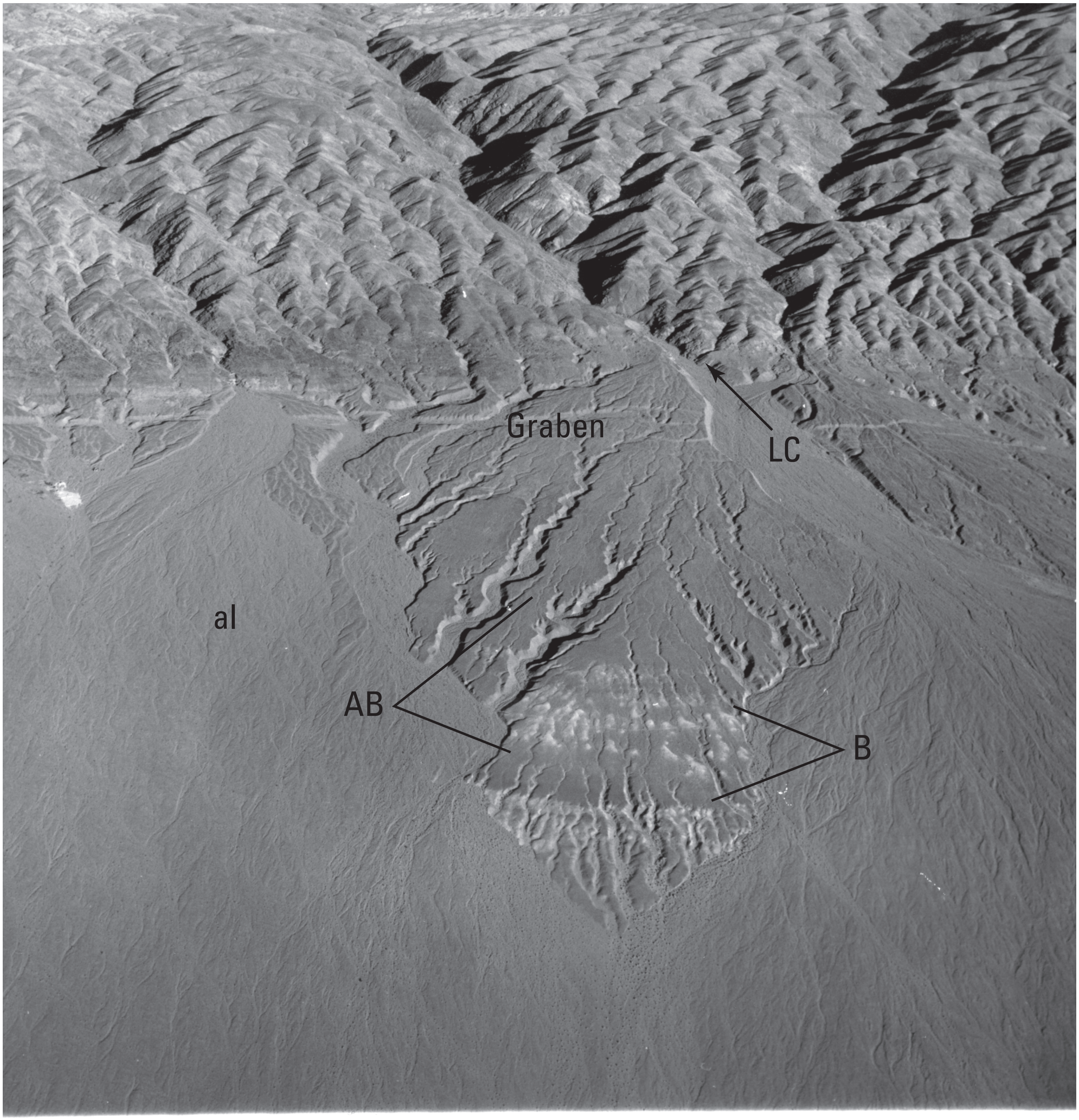


Figure 30. Oblique aerial view of the west side of the Slate Range and the east edge of Searles Valley. The range's gently sloping upper surface (tfs) is an exhumed thrust-fault surface (Smith and others, 1968, p. 10-11, figs. 10 and 11) that slopes toward Layton Canyon (LC). In the lower half of the photograph, remnants of unit AB form an elevated surface that preserves smaller remnants of light-colored silts and tufa layers of unit B; older gravel is exposed in most gullys dissecting these areas. The AB and B deposits stand 1 to 2 m higher than alluvial gravels of unit CD (slightly elevated, channeled surfaces) and active alluvium (al) in adjoining areas. Tufa 5 to 20 cm thick forms a medium-gray coating on the surface of light-colored sediments of unit B in foreground. Graben, which parallels Slate Range front (see fig. 35), is visible at head of fan. View is toward the east; unit B exposure about 360 m wide; location: plate 1, sec. J10-I.

Figure 31. Oblique aerial view of offshore lacustrine bars of the Searles Lake Formation in Valley Wells Wash area, about 10 km north-northeast of Trona. Note even curvature of bar crests, which vary in elevation by as much as 10 m. The bars were probably approximately parallel to, but not a uniform distance from, the lake shore. Crest of nearest bar in center of photograph composed of gravels of unit B, next prominent bar to its left composed of unit C, and dark bar in upper left corner is covered by unit B tufa, three samples of which yielded ^{14}C dates ranging from 13,650±500 to 15,520±60 yr B.P. Width of Valley Wells Wash where it cuts nearest bar is about 150 m. View toward southwest; present Searles (dry) Lake is to the south; photograph location: plate 1, sec. C15.

as marl and fine sand, eventually exposing a more resistant layer beneath them. Many of the areas mapped as outcrops of units AB, BC, and CD (pls. 1 to 4), which are generally composed of alluvium or coarse sand or gravel deposited in shallow water, were subsequently buried by many meters of finer sediment. Later, sublacustrine currents at intermediate depths (perhaps 2 to 10 m) apparently removed most of these soft sediments, inasmuch as evidence of subaerial erosion (channels, soils, or alluvium) is not found. Currents at all but the shallowest depths probably have limited ranges of erosional power that rarely exceed a certain competency. The upper limit of this competency would determine maximum sediment sizes that could be moved. In this way, the intermediate-depth currents would be capable of transporting the finer sediments to other areas, but incapable of moving the coarser fragments of the underlying layers. Although subaerial water-caused erosion processes exhibit a wide range of competencies, they tend to focus erosional energy into channels, which promotes dissection rather than exhumation. Examples of exhumation are the bar composed of subunit sa4 (sec. I32, pl. 4), the thin alluvial sheets of unit AB (secs. L1 and L12, pl. 1), the lacustrine delta composed of unit BC (secs. H13, H14, I18, and I19, pl. 3*A*), and the crests of bars composed of units B and C (secs. C10 and C15, pl. 2*A*).

The much-deeper canyons that developed on the flanks of the Spangler Hills and the Argus and Slate Ranges clearly predate deposition of the Searles Lake Formation and probably all gravels equivalent in age to the older gravel unit and the Christmas Canyon Formation. Deposits assigned to the oldest unit in the Searles Lake Formation rest on the bedrock flanks of Poison Canyon (pls. 3*A* and 3*B*) and in numerous other canyons around Searles Valley (pl. 1). Deposits assigned to the Christmas Canyon Formation and partly correlative deposits assigned to the older gravel unit are inset into canyons along the Slate and Argus Ranges and the Spangler Hills. If the lacustrine gravels that are interbedded in the older gravels exposed in two canyons of the Slate Range (noted in the description of that unit) are equivalent in age to the lacustrine deposits of the Christmas Canyon Formation that are overlain by the 0.64 Ma Lava Creek ash, the base of the older gravels in those canyons could have an age approaching or exceeding 1 Ma.

On the basis of subsurface evidence, the period between 2 Ma and 1 Ma is considered to have been characterized by intermediate to wet hydrologic regimes (fig. 32). Subsurface deposits indicating these environments are now 228 m to 425 m below the present surface of the lake (Smith and others, 1983, table 1). Possibly, streams in the canyons of the Slate and Argus Ranges and the Spangler Hills were initially graded to the base of this depth range. In that climatic setting, substantial downcutting of these canyons and deposition of large volumes of alluvial gravels on the flanks of these ranges probably took place. As the lacustrine basin filled, however, base level rose, causing younger alluvial deposits to begin filling the canyons eroded earlier, eventually building the fans to their presently observed gradients.

The earliest time that the presently extensive canyons along the flanks of these ranges could have been developed is limited only by the ages of the volcanic rocks in the northern parts of the Slate Range and the adjoining segment of the Argus Range (pl. 1). Those rocks were deposited prior to development of the Searles Valley Syncline, which subsurface data (Smith and others, 1983, p. 16) show occurred substantially before 3.2 Ma.

Neotectonics

Late Cenozoic faulting and tilting have affected virtually all of the deposits in Searles Valley. Layered deposits older than the Christmas Canyon Formation and the older gravel unit are moderately to strongly tilted and locally faulted (pl. 1). The Christmas Canyon Formation itself is tilted a few degrees where broad folds can be identified that lie astride of, and subparallel to, the Garlock Fault (Smith, 1991a, p. 617-620). Many segments of that fault have also placed deposits of the Christmas Canyon Formation adjacent to older or younger deposits, with scarps ranging from less than 1 m to more than 75 m high.

Fault scarps associated with the Garlock Fault along the south edge of Searles Valley are notably prominent. Clark (1973, maps E and F) plots the varying types of recently active fault features in this zone, noting stream channels that are offset laterally 15 to 25 m, scarps as high as 2.5 m, and numerous shutterridges, aligned notches, and benches. Reversals in vertical displacement along this fault occur over distances of less than a kilometer. In Searles Valley, the most prominent topographic indications of this fault lie in sections N11 and N12. In and west-southwest of section N11, the fault has created low, aligned ridges composed of gravels assigned to the Christmas Canyon Formation or the Searles Lake Formation. Many of these ridges are only a few centimeters high and, although easily seen on aerial photographs, are detectable on the ground only because they produce slight concentrations of fragments that are larger and darker than those found in the Holocene-age older alluvium that nearly covers them.

Within the area shown on plate 1, the Garlock Fault does not offset either the older alluvium or active alluvium units, although older alluvium locally can be traced to the base of scarps formed in older units, making it appear on a map as if that unit were also displaced. A particularly clear example of undisturbed older alluvium was observed about 100 m west of where the U.S. Navy road crosses the fault at the mouth of Christmas Canyon. There, the Garlock Fault consists of a single trace. A vertical excavation, about 30 cm deep, along the side of a small wash showed that the fault separates siltstone and sandstone of Tertiary age, on the south, from deposits assigned to units C and CD of the Searles Lake Formation. The fault zone is about 15 cm wide and dips 60° south. The fault trace is overlain by undisturbed older alluvium. Vertical displacement since unit C was deposited has been up on the south side. A left-lateral offset of the stream channel, which is cut into unit C, shows that about 8 m of slip has occurred. Displacement of 8 m in 10,000 years means an average lateral slip rate of 0.08 cm/yr, almost an order of magnitude lower than the 0.7-cm/yr horizontal slip rate suggested by Carter (1987, p. 135) for the Garlock Fault in an area 50 km to the west. Examples of stream-channel offsets in the area of plate 1 that exceed 8 m (Clark, 1973, maps E and F) all lie in gravels of the Christmas Canyon Formation. A 50- to 60-m left-lateral displacement of a stream channel by the Garlock Fault at a site 5 km west of the area of plate 1 (Clark, 1973, map E; Smith, 1964, p. 46) is in gravels possibly equivalent in age to the Christmas Canyon Formation. This would imply a minimum displacement rate of 0.01 cm/yr (60 m in 600 k.y.).

Along the west edge of the Slate Range, the Sand Canyon Thrust Fault and a normal fault are well exposed (Smith and others, 1968, p. 21). The thrust fault separates pre-Cenozoic bedrock units of different ages. The normal fault (extending from sec. G-22 to J-3, pl. 1) curves so that its trace remains a few hundred meters west of the lowest elevation bedrock exposures. It displaces all of the shoreline-bearing surfaces and the gravels of unit CD that postdate them (fig. 33). The steepest scarp segments average 35°. Most scarps are 4 to 8 m high, but near many washes they are a meter or less high. This was clearly documented in February 1984 by an exposure of this fault in a new channel cut in late 1983, where an unnamed wash had abandoned its former path and cut a new channel to its north (sec. G34-l). Vertical exposures that were still remarkably clean allowed detailed observations of the fault trace (fig. 34). Maximum offsets of identifiable beds in the lacustrine sediments of unit B or C are 0.4 m, yet the scarp formed in sediments of unit CD about 500 m north of these exposures exceeds 7 m in height, although that scarp may represent several offsets. A possible explanation is the following: Along the edges of mountain ranges, the sediment that underlies modern alluvial channels and rests on bedrock is thicker than alluvial sediment beneath areas adjacent to ridges, because the channels that are located at the mouths of bedrock canyons were also the sites of earlier channels and deeper incision. This fault scarp is presumed to be an expression of a normal fault of approximately uniform displacement in bedrock. The smaller offset of the present surface at the mouths of canyons could be because the bedrock displacement of the upthrown block was attenuated by upward splaying of the fault in thicker relatively unconsolidated late Cenozoic sediments. This would have distributed displacement over a wide zone normal to the fault, some of which may have consisted only of intergranular movements. Such attenuation would be approximately proportional to sediment thicknesses.

The larger clasts in the alluvial gravels of unit CD that have been up-faulted along the west edge of the Slate Range are characteristically pale brown and angular, with average sizes ranging from 10 to 25 cm; sediment colors on scarp faces are slightly lighter than on the flat unfaulted surfaces, but no soils were developed. The uplifted surfaces have relict, now-inactive channels that are as deep as 1 m and filled with

Figure 32. Simplified plot showing periods characterized by wet, intermediate, and dry climates in the part of southeastern California including the drainage basin of the Owens River during the past 3.2 m.y. (after Smith, 1984, table 1). These different regimes were expressed in the succession of water bodies in the Owens River System, namely the lakes in Owens, China, Searles, Panamint, and Death Valleys. During dry regimes, which includes the present regime, the Owens River normally supplied enough water only to partially or totally fill Owens Lake, with rarely a small overflow into China Lake. During intermediate regimes, the Owens River flow typically filled Owens, China, and Searles Lakes, with rarely a little overflow into Panamint Lake. During wet regimes, the Owens River flow would have been great enough to fill all of Owens, China, Searles, and Panamint Lakes, and the overflow even formed a large lake in Death Valley (Lake Manly).

colluvium and wind-blown sand. Those channels are aligned with the counterpart relict channels on the downthrown blocks, indicating no lateral displacement.

Where active alluvial channels dissect these normal fault scarps, the modern alluvial surface and one or two older alluvial surfaces that are 2 m or less higher are not faulted; the higher (older) of these two has the unchanneled surface that is characteristic of the older alluvium unit, and its surface commonly lies 1 m to 1.5 m above the modern wash. These relations show that displacements along this fault occurred after deposition of unit CD and probably before deposition of the older alluvium, meaning that faulting probably ceased during or shortly after the Holocene deposition of unit D.

South of this normal fault, a narrow graben and several normal faults displace deposits of the Searles Lake Formation (sec. J2 to J28, pl. 1; fig. 35*A*). The graben, described elsewhere (Smith, 1966a, p. 65-75, fig. 8; Smith and others, 1968, p. 23-24), is a little more than 3 km long, and photogrammetrically determined profiles show that it has an average width of about 30 m and depth of 5 m. South of the graben, a zone of less systematic normal faulting continues for another 3.5 km. The overall trend of the graben is nearly north and straight, but in detail the boundary faults are sinuous and composed of nearly aligned, left-stepping and overlapping en echelon fractures (fig. 35*B*). Faults outside and south of the main boundary faults of the graben have characteristics that are similar to the boundary faults. The faults constituting the graben are apparently of Holocene age. They displace deposits of the Searles Lake Formation as young as unit B, and the normal faults that extend south of the graben displace gravels of unit CD. The lack of deposits belonging to unit C within the boundaries of the graben, which would have acted as a trap for sediments when the lake that deposited unit C stood above the graben's elevation, further supports the conclusion that the graben and associated faults are Holocene in age and possibly middle Holocene. As with the normal fault exposed north of the graben, sediments mapped as older alluvium (unit oal) and active alluvium (unit al) are not displaced by this fault.

Smith and others (1968, p. 21, 24) tentatively attributed the graben and associated faults to normal displacements on the low-angle Sand Canyon Thrust Fault (pl. 1) or to compaction of the valley fill. While displacements along the thrust fault might explain the graben, which overlies the buried trace of that thrust, this mechanism cannot explain the normal fault to the north, which offsets sediments that clearly rest on the upper plate of that thrust. The compaction mechanism is also unattractive as an explanation because it would be expected to result in the greatest displacements being at the mouths of canyons where the fill is thickest, rather than the opposite. Possibly, normal displacements along a concealed low-angle

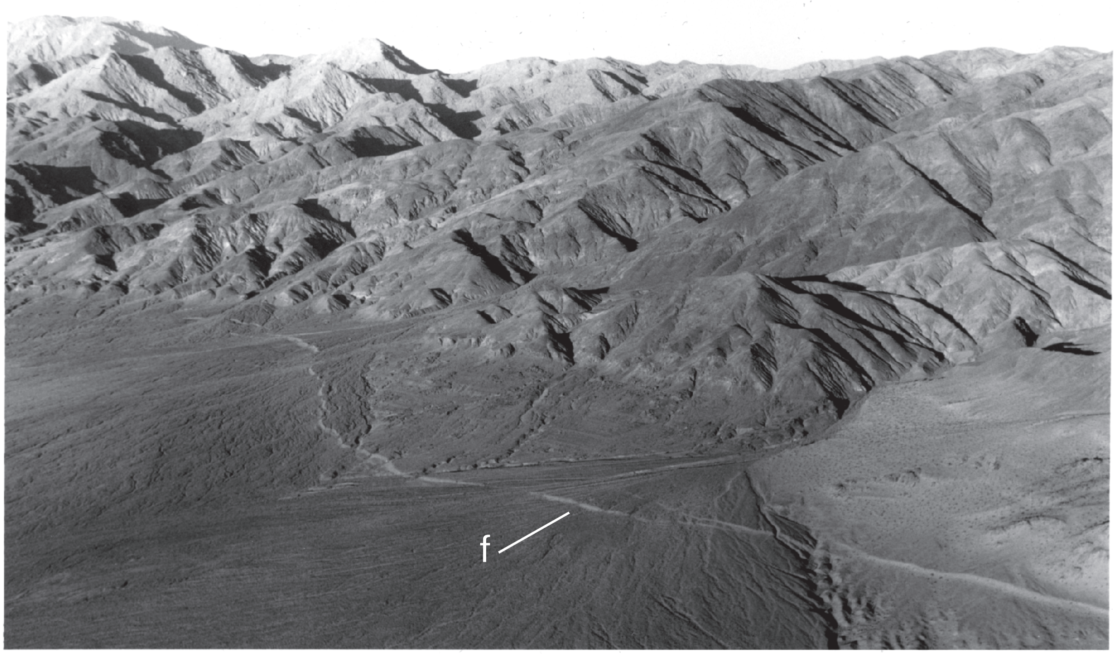


Figure 33. Oblique aerial view of the west edge of the Slate Range, showing scarp of normal fault. The west-dipping fault displaces sediments ranging in age from unit B to unit CD. Scarp is as much as 8 m high, but tends to be lower where it crosses mouths of canyons. View is toward northeast; the lighter-colored Panamint Range forms most of the skyline. Where scarp cuts alluvial fan in lower center of photograph (labeled f), location is plate 1, sec. G27-m.

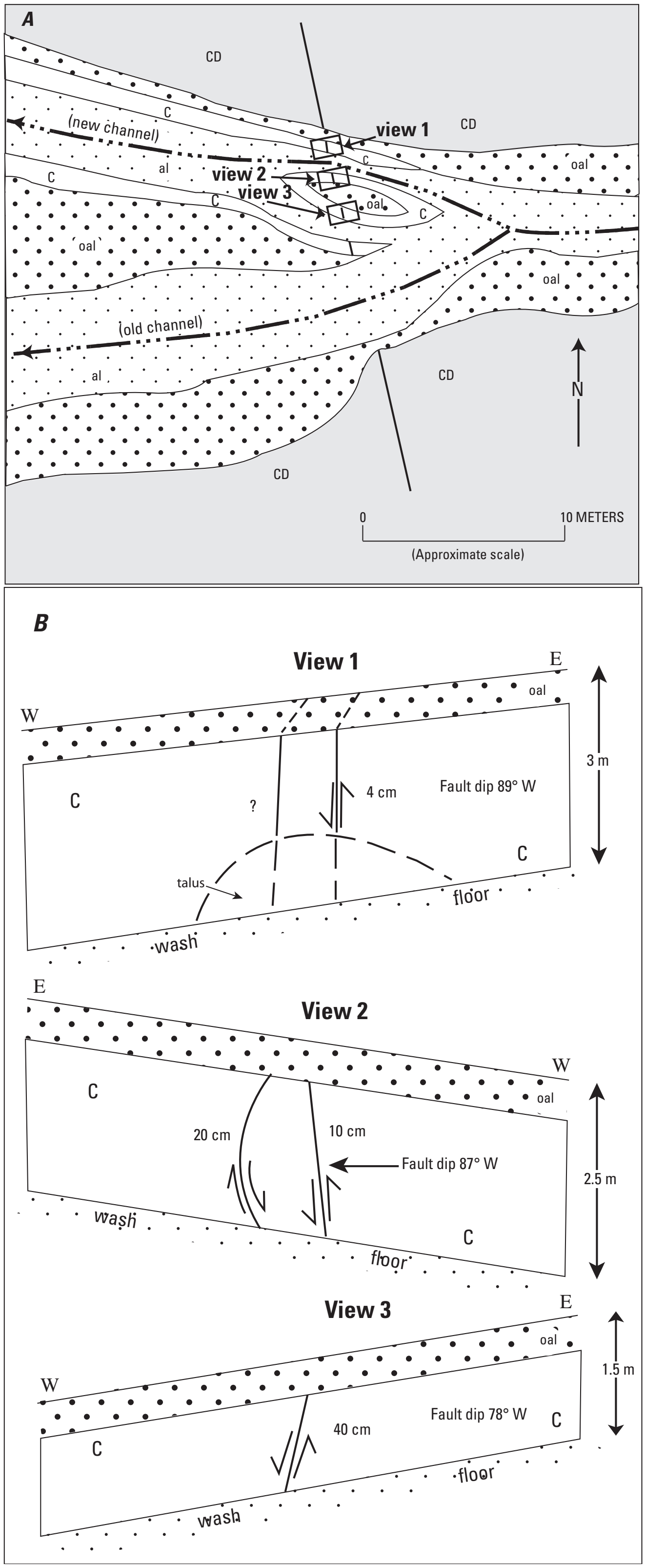


Figure 34. Field sketches of normal fault (medium line) exposed on sides of channel recently eroded through sediments of unit CD and older alluvium (oal) and floored by active alluvium (al). Location: plate 1, sec. G34-I. *A*, Map view, showing locations of the three views (vertical profiles) of channel walls. *B*, Sketches of channel walls showing fault traces and sense of movement. Displaced sediments are mapped as unit C, but they could be unit B; overlying older alluvium is not displaced (although some cracks have propagated to the surface). Vertical displacements of identifiable horizons are indicated; they range from 4 cm to 40 cm. Note that one strand of the fault in view 2 shows reverse displacement.

fault, parallel to but west of the Sand Canyon Thrust Fault, caused extension along both the normal fault and the graben, but direct evidence of such a fault was not seen.

The short fault that is subparallel to the Garlock Fault and extends from section L32-m to section N2-r in southern Searles Valley is probably a left-lateral strike-slip fault (like the Garlock Fault), although good evidence was not found. This fault is straight, and vertical displacements along its trace vary—two common characteristics of strike-slip faults. Sediments assigned to older gravels and unit B of the Searles Lake Formation are displaced, and playa silts along its southeast side document the creation of a sag pond.

The sinuous fault along the southeast side of the Spangler Hills (K31 to K23) is a normal fault. The fault trace is expressed topographically and by linear zones of caliche, and in a few places the fault surface is exposed, revealing high-angle slickensides. Dips on these exposed surfaces range from 50° to 80° southeast, with the southeast block being consistently depressed. The fault's age is Quaternary, but late Quaternary activity is not provable. Only deposits correlated with the Christmas Canyon Formation and bedrock are clearly faulted (tufa and sediments of unit A of the Searles Lake Formation also may be faulted, but the exposures are inadequate to be certain).

Folding of late Cenozoic sediments is evident in several parts of the valley. Along the Garlock Fault, an east-northeast-trending anticline and two parallel flanking synclines can be identified from the elevations of the basal contacts of the Christmas Canyon Formation (Smith, 1991a, p. 617-619). Deformation during the 20th century along known geologic structures is also detectable where benchmark lines have been resurveyed (Smith and Church, 1980, table 4). Crustal movements appear also to be causing continuing elevation of the crest of the Slate Range anticline and depression of the troughs of the Searles Valley and Pilot Knob Valley Synclines at long-term (10-100 years) average rates of about 0.015 cm/km/yr. Folding or tilting may also be indicated by differences in the elevation of the top shoreline. In most places, however, the rate of tilting cannot be determined because this shoreline is the product of erosion during each of the periods when overflow occurred, and it is difficult to establish accurately either the level or age of the lake primarily responsible for this feature.

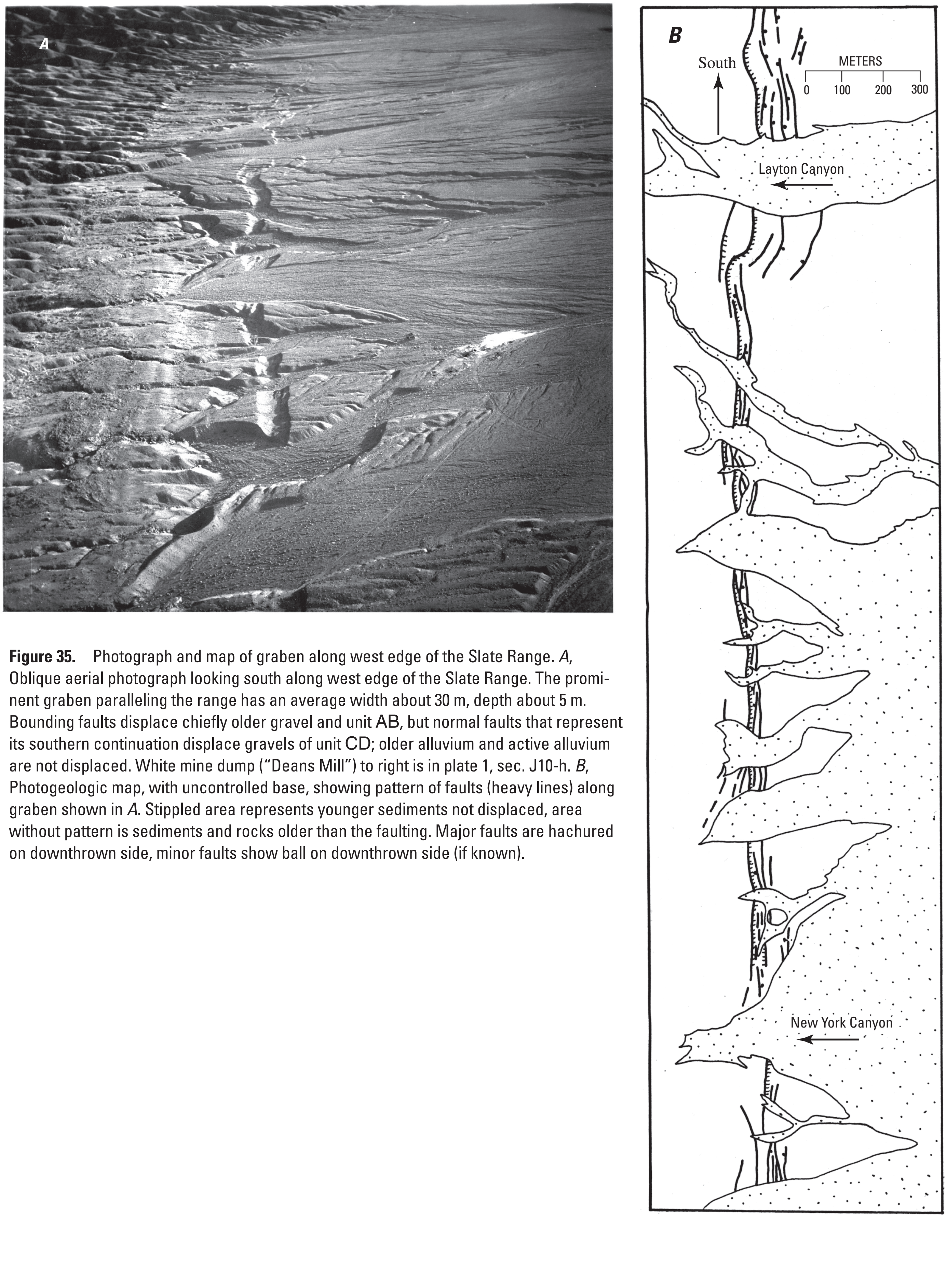


Figure 35. Photograph and map of graben along west edge of the Slate Range. *A*, Oblique aerial photograph looking south along west edge of the Slate Range. The prominent graben paralleling the range has an average width about 30 m, depth about 5 m. Bounding faults displace chiefly older gravel and unit AB, but normal faults that represent its southern continuation displace gravels of unit CD; older alluvium and active alluvium are not displaced. White mine dump ("Deans Mill") to right is in plate 1, sec. J10-h. *B*, Photogeologic map, with uncontrolled base, showing pattern of faults (heavy lines) along graben shown in *A*. Stippled area represents younger sediments not displaced, area without pattern is sediments and rocks older than the faulting. Major faults are hachured on downthrown side, minor faults show ball on downthrown side (if known).

In most areas, the elevations of the uppermost outcrops of lacustrine sediments, determined from 40-ft contours, are not considered more accurate than about +20 ft (6 m). In areas characterized by tufa benches, where water level at the highest shoreline can be more precisely reconstructed, a barometric survey of shorelines that are near benchmarks only indicated small and questionable elevation differences. Uplift may be indicated in one area that lies just north of the Garlock Fault and near Christmas Canyon (sec. O4-e), where lacustrine gravels assigned to unit A of the Searles Lake Formation are mapped to an elevation that is 10 m above the probable top shoreline elevation elsewhere in the valley. Rates of uplift indicated by this observation would range from 0.007 to 0.03 cm/yr, depending on whether the age of the gravels is taken to be near the beginning or end of that unit's depositional period.

Paleolimnology

Many aspects of the physical limnology of Searles Lake during deposition of the Searles Lake Formation can be reconstructed from the evidence described in this report, especially when supplemented by evidence obtained from the subsurface record (Smith, 1979). During relatively dilute stages, the lake's salinity level can be inferred from fossils, and its ionic composition can be reconstructed from the composition of any salts deposited later. Lakes that were density stratified as a result of differing concentrations of salts in the upper and lower layers are implied by laminated sediments, and horizontal salinity gradients are revealed by the zonation of fossils. The character of the clastic and chemical sediments—their physical, textural, and mineralogical properties—indicate the nature of both the low- and high-energy environments that existed in the deep and shallow parts of the water body, respectively. Storm-wind directions can be inferred from the location and orientation of a sand and gravel bar wherever the source of its components can be identified. Each of these paleolimnological attributes helps to infer the lake characteristics and climates that existed during successive periods, and these are discussed in a later section. Additional criteria useful in reconstructing the paleolimnological record offered by the lacustrine deposits are reviewed by Currey (1990).

Lake-Water Chemistry and Density Stratification

As indicated by subsurface saline deposits, the water in the lake occupying Searles Valley during deposition of the Searles Lake Formation (as well as all of the periods extending back to 300 ka) was dominated by sodium, chloride, carbonate plus bicarbonate, and sulfate. The ostracode populations lead to a similar conclusion. The lake was also alkaline, as all of the subsurface salt layers that formed at times of lake shrinkage or desiccation contain high percentages of sodium carbonate-bearing salts, and many layers contain sodium borates (Smith, 1979), all being salts composed of components that dissociate in water into strong bases and weak acids. As a 1-percent Na_2CO_3 solution has a pH near 11.6 (Handbook of Chemistry and Physics, 1966, p. D80), it is probable that Searles Lake was alkaline even at more dilute stages. Also, Owens and Mono Lakes, the modern termini of the drainages that provided most of the water and dissolved solids to Pleistocene Searles Lake, are carbonate rich and alkaline. The major-anion mole percentages of the Upper Salt and Lower Salt (salts plus brines), and the waters of Mono Lake and (predesiccation) Owens Lake, are:

	CO_3+HCO_3	SO_4	Cl
Upper Salt (Smith, 1979, p. 64)	16	11	73
Lower Salt (Smith, 1979, p. 47)	36	7	57
Mono Lake (Mason, 1967, table 9)	37	11	52
Owens Lake (Gale, 1914, p. 258, column 9)	31	9	60

Mono Lake waters have a pH near 9.5 (unpub. data, samples collected August 1956), and Owens Lake brines (in 1969-1971, after solution of the top 0.2 m of salts) had pH values ranging from 9.6 to 11.0 (Friedman and others, 1976, table 1). Interstitial brines from Searles Lake have pH values mostly between 9.2 and 9.5 (Smith, 1979, tables 9 and 16).

Stratified lakes in which the stratification is caused by salinity differences can be very stable, lasting years or even centuries. Many temperate-region lakes become stratified each year because of temperature-caused changes in density whose numerical expressions involve numbers in the third decimal place; salinity stratification can be a result of density differences that involve numbers in the second or even first decimal place. For example, Big Soda Lake, Nevada, is chemically stratified with density contrasts of about 0.04 g/cm^3, and calculations suggest that it could require as much as a century for wind energy to mix the upper and lower layers (Hutchinson, 1937, p. 78, 125; Hutchinson, 1957, p. 512). Nevertheless, in order for Searles Lake to have retained a stratified structure for many hundreds or several thousands of years, a periodic renewal of its density stratification was probably required. Annual flooding of the lake surface by fresh water during the early-summer melting of Sierra Nevada snow might have prolonged the stratified condition, with the ensuing evaporation removing most of the fresh water before it was mixed extensively down into the saline zone. But even this process, with some dilution of the underlying saline water body each year, would have eventually converted the lower saline layer to one that would more easily mix with the less dense annual influx. However, the most extreme dry period of each century or two might have evaporated all of that year's annual inflow layer plus part of the underlying saline layer, restoring that deeper layer to its former density and allowing stratification to continue for an additional period.

After periods of persistent rain, outcropping fine-grained sediments assigned to units B and C of the Searles Lake Formation sometimes develop a zone of efflorescent salts on, or a few centimeters beneath, their outer surfaces. The efflorescent salts are apparently crystallized from rain waters that first penetrated the outer layers of the outcrop sediments and then migrated back toward the surface as a result of capillary processes, bringing trace amounts of any soluble salts in the sediments. Sediments of unit A rarely develop efflorescences, probably because any salts they contained were leached out long ago. This eliminates an alternative explanation—that efflorescent salts are recycled by wind-blown dust. Determining the mineralogy of these salts by X-ray diffraction is believed, therefore, to indicate the composition of salts that were in the waters trapped in the interstitial spaces of the sediment at the time of their deposition. These mineral compositions thus serve as a crude indicator of the composition of the lake waters at the time of deposition (Smith, 1966b). Halite (NaCl), thermonatrite ($Na_2CO_3 \bullet H_2O$), thenardite (Na_2SO_4), and ulexite ($NaCaB_5O_9 \bullet 8H_2O$) are the most common efflorescences. Gypsum ($CaSO_4 \bullet 2H_2O$) is locally common in some units, but rather than forming efflorescences it forms eudedral crystals a centimeter or more long; they may have been produced by a different process, possibly involving the oxidation of sulfides in the sediments (pyrite has been noted in subsurface sediments).

Some stratigraphic units, even from widely separated parts of the valley, consistently produce efflorescences having similar mineralogies, and this is taken to be good evidence of the chemical composition of the lake water in which they were deposited. Halite that is clearly secondary is nearly ubiquitous in fine-grained sediments below the level reached by the lake responsible for unit D. That middle Holocene lake was quite saline, and salt from it impregnated and cemented the upper few centimeters of all sediments on its floor, especially those of units B and C, making them highly resilient.

Low-Energy Environments

Fine-grained lacustrine sediments exposed as outcrops in Searles Valley represent low-energy, nearly current-free sites of deposition. Because current energy was low, clastic sedimentation rates were also low, and chemical sediments composed chiefly of carbonates contributed significantly to the lithologic character of the deposit. Every sample of fine-grained lacustrine sediment tested with acid for its carbonate content effervesced vigorously. However, the amount of carbonate in those sediments, judging from their color, response to acid, and chalky feel, varies both stratigraphically and areally.

Stratigraphic variations in the carbonate content of deep-water sediments in Searles Valley appear to reflect variations in the volume of the lake's inflow, which is inferred to have been the major source of variation in the amounts of available dissolved Ca. The concentration of Ca in those inflowing waters would have tended to be constant because it was controlled by the solubility of calcite, with which it was saturated, a fact known to be true because calcite is also abundantly represented in the subsurface sediments of both upstream lakes, China Lake (Smith and Pratt, 1957, p. 14-25) and Owens lake (Bischoff and others, 1997, figs. 2, 3). Quantitative estimates of the amounts of carbonate deposited in Searles Valley have not been made, but the persistently calcareous character of the perennial-lake sediments and the nearshore tabular tufa deposits indicate its constant replenishment by inflowing streams.

Areal variations in the carbonate content of low-energy deposits, like those of unit A, appear to be a consequence of the lack of stratification and the development of "chemical deltas" near the inlet regions. As discussed in the earlier section on the Searles Lake Formation, chemical deltas developed in the basin where inflowing, relatively fresh, Ca-bearing water partially or completely mixed with water of the alkaline lake near its inlet, resulting in the rapid precipitation of $CaCO_3$ minerals near the mixing sites. During these periods, carbonate available for deposition in other parts of the basin was reduced.

In contrast, the common presence of aragonite laminae in the low-energy deposits observed in both subsurface (Smith and Haines, 1964, p. 52, fig. 14) and exposed sediments, like those of units B and C (fig. 10), is interpreted to mean that the lake was alkaline, frequently stratified, and periodically receiving large amounts of fresh, Ca-bearing waters. This combination of characteristics allowed the Ca in inflowing waters to be first spread throughout most of the basin, because it was dissolved in the relatively fresh, less dense upper layer, and then precipitated as aragonite when the underlying denser and alkaline waters mixed with the fresher inflowing waters along the chemocline.

Although the local abundance of very fine grained dolomite in both subsurface and exposed sediments could also be produced by the mixing of dissimilar waters, the largest concentrations of dolomite in subsurface mud layers are near the contacts with saline layers, in layers formed when lake salinity was either approaching or retreating from salt-saturation levels (Smith, 1979, p. 81). In this study, when outcrop evidence indicates a period of lake contraction, dolomite-rich zones in outcropping sediments are considered supporting evidence of a shrinking lake whose waters had a high pH and increased salinity, yet which had to receive periodic influxes of fresh Mg- and Ca-bearing waters for dolomite crystallization to continue. Some of the processes that control the crystallization of lacustrine dolomite, however, are not well understood.

These inferences are based on relations such as those found between the lithologic, chemical, and mineralogic data from core GS-16 (Haines, 1959, p. 245-268; Smith, 1979, table 13; and unpub. data). Figure 36 shows the character and distribution of laminated and unlaminated sections of the Parting Mud in that core. In most cores of the Parting Mud, segments of finely laminated mud are found primarily in its upper third. Dissolved Ca has a very low solubility once mixed with alkaline waters, and aragonitic laminae require the periodic replenishment of the lake's Ca after most of the previously introduced content has precipitated. Finely spaced laminae, therefore, require a frequent resupply of enough fresh water to re-create stratified conditions and replace the previously precipitated Ca. Counts of white laminae in thin sections from the upper third of the Parting Mud, however, show that laminae represent only about a third of the years that ^{14}C ages suggest are represented within an interval, meaning that only one out of three years produced enough inflowing Ca for distinct laminae to be deposited in the basin's center. Periods of high, yet still-increasing inflow thus introduce increasing amounts of dissolved Ca, which then precipitates as calcite, dolomite, or aragonite. In core GS-16, two intervals of upwardly increasing CaO are separated by an interval of decreasing CaO, and the two thickest sections of finely laminated sediments are those characterized by the next upward increases in CaO. This inferred history of a lacustrine fluctuation agrees with the evidence derived from outcrop data, as will be shown later, as well as with fossil pollen evidence of climate changes (Roosma, 1958).

The acid-insoluble component of low-energy deposits (fig. 36) also shows trends that are significant and independently confirm the fluctuations in the lake levels inferred from outcrops of units A, B, BC, and C. The acid-insoluble component primarily represents the clastic fraction in the layers of low-energy deposits that was mostly derived from the materials surrounding Searles Valley (Smith, 1979, p. 53, 67, 81-82). At a fixed, midbasin site (such as represented by core GS-16, fig. 36), the percentage of acid-insoluble material reflects chiefly the proximity of that site to the surrounding sources of clastic materials—shallow water sandy zones and the enclosing beaches and bedrock. Therefore, increasing clastic percentages should accompany decreasing CaO percentages, as both indicate decreasing inflow and lake size. In core GS-16, this inverse relation is well illustrated.

The estimated abundances of aragonite and dolomite also reflect the same fluctuation in lake size and salinity (fig. 36). Samples containing major to intermediate amounts of aragonite (or its postdiagenesis products, gaylussite and pirssonite) came from horizons that were characterized by fine or coarse laminae, sediments that now contain 10 to 18 percent CaO; only one sample falls below this range. The dolomite content, a measure of increasing salinity, remains at intermediate levels throughout much of the interval, but it is most abundant in the sample (from 73 to 74 ft) that also contains the lowest CaO and highest acid insoluble percentages. These criteria indicate the interval between 73 and 74 ft in core GS-16 to be representative of a shrinking lake that was not stratified (no aragonite) and receiving less inflow (decreasing CaO percentage), causing the shallow-water source of clastics to move closer to the sample site (increasing acid insolubles) and increasing its salinity (increasing dolomite).

High-Energy Environments

The characteristics of sediments deposited in the shallow waters of Pleistocene Searles Lake were controlled primarily by the current strengths and the local supply of clastic material. Reconstruction of the limnologic nature of former lakes, by studies of the sediments in their high-energy environments, chiefly produces information concerning changes in the relative intensities and directions of wind-driven currents during various periods and in various parts of the basin.

Changes with time in the maximum sizes of fragments in gravel beaches and bars and along wave-eroded shorelines were noted earlier. Many of the deposits of gravel in bars and along shorelines, as well as lag gravels that were depleted of their smaller fragments by waves, cannot be confidently related to the stratigraphy that is based largely on finer sediments. However, some gravel deposits can be traced laterally or downhill into finer facies, especially in the Valley Wells Wash area (pl. 2*A*), along the north and east edges of the Spangler Hills (pls. 3*A* and 4), and in many of the longer canyons of the Argus and Slate Ranges (pl. 1). In stratigraphic sequences that can be traced with confidence, one finds that gravel-fragment sizes decrease with decreasing age. For this reason, one can hypothesize that even where stratigraphic control is equivocal or absent, gravel deposits of unit B, for example, will probably be less coarse-grained than nearby coarse-grained gravels of unit A, and the successively younger gravels of units C and D will be less coarse-grained than those of unit A and unit B. If this working hypothesis is valid, it means that storm-wind velocities during deposition of the Searles Lake Formation were statistically at their maximum during deposition of unit A, and they diminished during successively later periods.

Within unit A, however, fragment sizes in the only well-exposed gravel bar deposited during unit A time (pl. 4, sec. I32-q) are coarsest and most angular in the youngest subunit (sa4), suggesting that storm-wind intensities increased as deposition of that unit progressed, then later decreased during deposition of units B, C, and D. In his study of Pleistocene Lake Lahontan, Nevada, Morrison (1964, p. 29, 99) notes that gravels in the Eetza Formation (Eetza Alloformation of Morrison, 1991), near the middle of the several formations assigned to the mostly lacustrine Lahontan Valley Group (Lake Lahontan Allogroup of Morrison, 1991), are coarser than any lacustrine gravels of younger deposits, but he finds the coarsest gravels to be at the base of that formation. If the Eetza Formation and younger units of the Lahontan Valley Group are time-correlatives of the Searles Lake Formation, the late Pleistocene history of windiness indicated in the two regions is broadly similar but different in this detail.

Although the high-energy environment was dominated by coarse-fragment sedimentation, large amounts of $CaCO_3$ were also deposited in the matrix of the coarse deposits. Some of the carbonate is still preserved as marl that fills interstitial spaces or forms thin beds between gravel layers; both lithologies indicate that (short?) periods of carbonate deposition interrupted the (longer?) episodes of coarse-fragment deposition. Some carbonate, however, may be younger because it is now found as a translucent calcite lining that fills much of the empty space between clastic fragments and cements them together. In some instances, this calcite constitutes an estimated 5 (volume) percent of the gravel. The volume of water required to introduce that much $CaCO_3$ is enormous. For example, 1 m^3 of gravel containing 5 (volume) percent calcite ($13.6x10^4$ g) would have

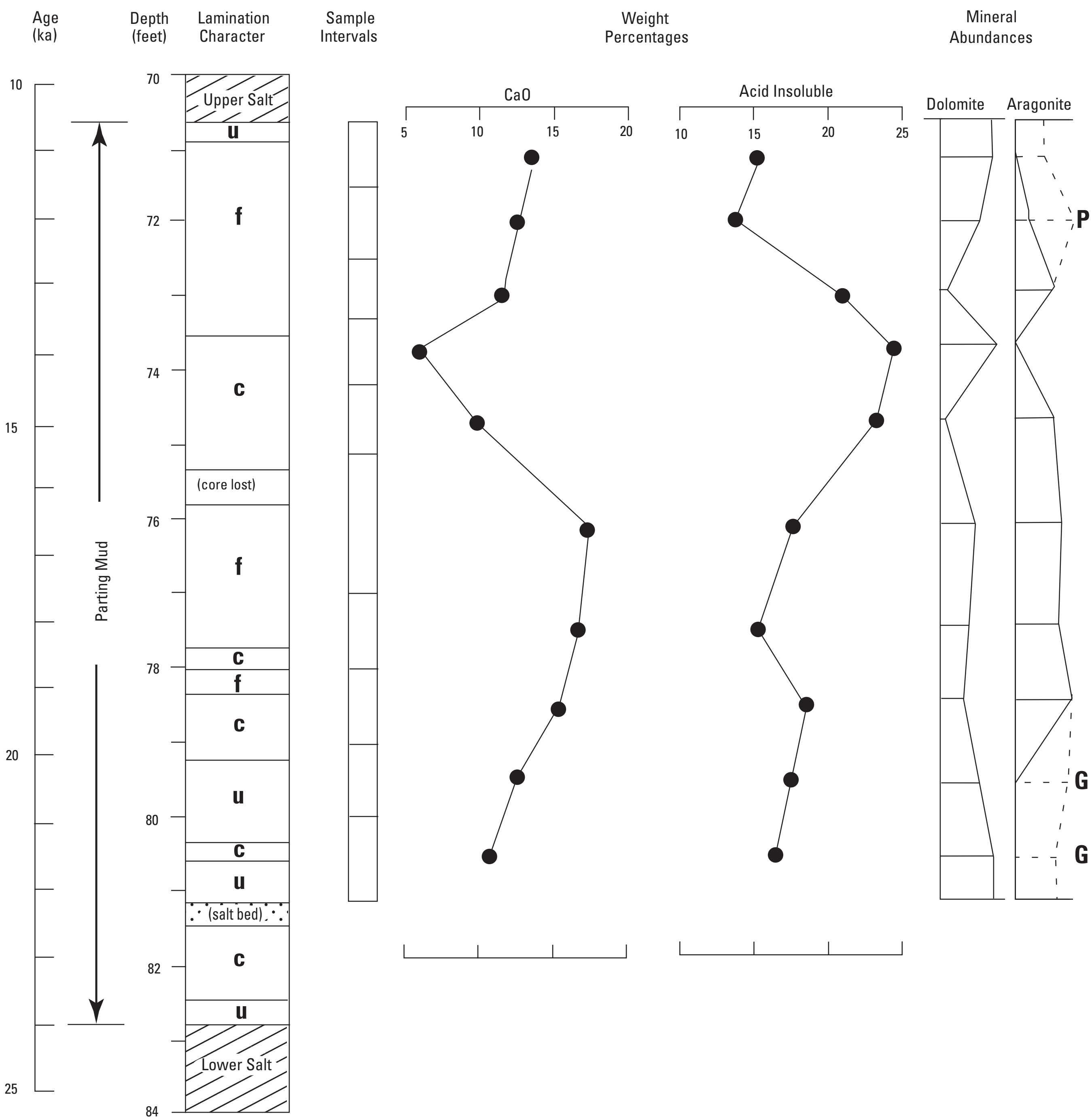


Figure 36. Diagrams showing lithologic, chemical, and mineralogic characteristics of subsurface Parting Mud in core GS-16 at Searles Lake (location: plate 1, corner of secs. 26, 27, 34, 35; see Haines, 1959, p. 245-268). Ages are interpolated from the ages of the basal and top contacts of the Parting Mud (24 ka and 10.5 ka). Bedding characteristics of mud shown as u (unlaminated), c (coarsely laminated), or f (finely laminated) as described in text. Weight percentages of CaO and acid-insoluble material in samples of GS-16 (sampled intervals as shown) from unpublished data (H. Almond, analyst, written commun., October 1956). Mineral abundances from Smith (1979, table 13) and unpublished data; dashed lines on aragonite-abundance diagram labeled P and G represent abundances of diagenetic pirssonite ($CaCO_3 \cdot Na_2CO_3 \cdot 2H_2O$) and gaylussite ($CaCO_3 \cdot Na_2CO_3 \cdot 5H_2O$), respectively. Those two minerals probably consumed part or all of the primary aragonite, explaining its diminished abundance in those sections of the core.

required about 9,700 m^3 of saturated fresh water to transport that amount of $CaCO_3$ to the site of deposition. Transport by alkaline lake water would require an even greater volume of saturated water. If the lake water was 5° cooler than today, and the evaporation rate was 1.2 m per year (Smith and Street-Perrott, 1983, table 10-20), each m^2 of lake surface would evaporate 9,700 m^3 of water in about 8,100 years.

In a few areas where coarse sand was being deposited at the edge of the enlarged Searles Lake, defluidization structures formed (fig. 37). In Searles Valley, these structures mostly take the form of vertical columns of calcite-cemented sand, 10 to 50 cm high and 3 to 10 cm in diameter. Similar structures now form around the edges of carbonate-rich Mono Lake (salinity 5 to 10 percent) where fresh, calcium-bearing ground water impinges on the more dense lake water that impregnates the sand around the edges of the lake (Cloud and Lajoie, 1980). These columns form as follows: (1) Because of the density contrast between the saline-lake water and ground water, encroaching fresh ground water is forced upward through the overlying sandy sediments, forming vertical conduits. (2) Mixing of ground and lake waters occurs in the sediment forming the edges of the conduits. (3) This process supersaturates the water mixture with calcite, which precipitates in the interstices along the conduit's edge and cements the vertical sides. Much evidence leads to the conclusion that Searles Lake had, at times, a composition and salinity similar to that of modern Mono Lake and that the same processes were at work. In Searles Valley, excellent examples of defluidization structures occur in sec. C3-r (2,070 ft) and sec. L9-q (1,860 ft). The significance of these structures is that they indicate sediments deposited in a lake-edge environment, that the lake at that level was alkaline and had a moderately high salinity, and that the ground-water table at that time and place was virtually at the surface.

Bar-Gravel Transport Directions

The wide variety of rocks exposed in the mountains surrounding Searles Valley (fig. 1*B*) provides a means of reconstructing the sources of the gravel in its lacustrine bars. The Slate Range is lithologically the most diverse. Paleozoic limestone and dolomite that are partially covered by Cenozoic basalt and gravel crop out in the northern part of the range, Mesozoic plutonic rock dominates its central area, and Mesozoic metavolcanic rock and Precambrian(?) metaplutonic and schistose rock crop out in its southern part (Smith and others, 1968, pl. 1). The Lava Mountains are mostly composed of Cenozoic arkosic sandstone and volcanic rocks (Smith, 1964, pl. 1); the unnamed hills to their northeast expose large areas of the gravel and sand facies of the Christmas Canyon Formation (pl. 1), most easily identified from its vesicular basalt cobbles and boulders. The Spangler Hills are composed mostly of Mesozoic plutonic rock, plus a small area of stretched conglomerate; they are intruded by mostly mafic hypabyssal dike rock (Smith, 1962, p. 90-100). The part of the Argus Range draining into Searles Valley is also composed mostly of Mesozoic plutonic rock, but mafic hypabyssal dike rock crops out in the range's south end and Cenozoic basalt partially covers the plutonic rock of its north end.

The locations of the most prominent lacustrine bars in Searles Valley are plotted in figure 38*A*, and their elevations and locations are listed in table 8. All but three of the listed bars are close to the north or south ends of the valley. Because the rock assemblages from the surrounding mountains are so different, the fragment assemblages found in each bar indicate clearly the source area and allow a generalized reconstruction of Pleistocene storm-wind directions. Many bars derived material from two sides of the valley, but the directions of transport listed in table 8 are believed to have been dominant because the distinctive components were those determined near the middle of the bar.

Reconstructions of storm-wind directions are based on the following assumptions and conceptions: (1) In Searles Valley today, winds are usually strongest downwind from the low points in the surrounding mountains. Therefore, Pleistocene winds from the west are assumed to have been strongest east of the inlet from China Lake, which is the lowest part of the mountains bounding the west side of the valley (fig. 1*B*). Winds from the east seem likely to have been strongest west of Layton Pass, the lowest part of the Slate Range (which is due east of the inlet from China Lake). Winds from either of these directions would probably have promoted oppositely rotating gyres in the north and south halves of Searles Lake. Storm winds from the north or south do not seem to be represented by many, if any, bars in the basin (fig. 38*A*). (2) The most effective erosion and bar deposition probably occurred where winds entered the basin from a direction that provided a large fetch. (3) Wave erosion and the longshore drift that transported the eroded material long distances required wind-caused currents that arrived from a direction oblique to the shore being eroded. (4) Studies show that in lakes, wind-driven currents usually maintain their strength and orientation only down to depths of 5 m or less (Hutchinson, 1957, p. 286-289), which probably approximates the depth range in which these lacustrine bars in Searles Valley were constructed. While staying within this depth range, the longshore currents constructed bars with curving trends that roughly parallel the shore but in most instances only approximate the detailed shoreline configurations (fig. 31).

At elevations near 2,200 ft and 2,100 ft (fig. 38*B*), bars assigned to units AB and C in the north end of the valley (secs. A28 and C3, table 8) were built mostly from clastic fragments transported northeastward from the Argus Range; bars in the southern part of the valley assigned to these units are constructed from clastics transported westward from the Lava Mountains (sec. N8-d, table 8) and Slate Range (sec. L15-q). However, when the lake fell to levels between 2,000 ft and 1,800 ft, debris forming bars mapped as units B and C in the north end of the valley was eroded from the northern Slate Range and transported northwest and west, and bars mapped as unit C in the south part of the valley derived their components from the southern Slate Range and transported them southwest by longshore currents.

Exceptions to these generalizations must be made for the bar gravels mapped as belonging to unit A. The bar near 2,200 ft mapped as part of unit A (secs. L22 and L27) is composed of fragments eroded from the Christmas Canyon Formation and transported eastward, but this bar may have been assigned to the wrong stratigraphic unit because it lies in an area without other lacustrine sediments for reference. The bar mapped as unit A near 2,000 ft elevation (H21-q,r) was built by wind-driven currents that carried the fragments northwest, and the one near 1,800 ft (I32-m,l,q) transported debris from the Spangler Hills toward the southeast.

Although the meteorologically significant topography did not change during deposition of the Searles Lake Formation, the shape of the lake did as it expanded and contracted. These changes must have altered the circulation patterns in the lake, and this could be responsible for some of the apparently conflicting evidence of storm-wind directions. However, because bars account for a very small percentage of the lacustrine deposits in the valley, construction of them probably occurred only when the strength of wind-generated currents greatly exceeded that of current resulting from normal circulation. From this, one can conclude that bar-forming currents occurred only during the strongest windstorms and did not necessarily reflect the prevailing winds, which probably came from the west as inferred from the distribution of tufa in the valley.

The lacustrine bars formed during deposition of units AB and C, when the lake level was near 2,200 ft and 2,100 ft (fig. 38*B*), suggest that the storm winds came from northeast, east, or southeast, causing erosion along the western shores. Near the north end of the lake, where a clockwise gyre presumably formed, eroded debris was transported by currents moving northeast and then east and southeast as the shoreline configuration required. Correlative-aged debris eroded from the southern part of the lake was transported southwest. The two bars at lower levels mapped as part of unit A—near the 2,000-ft level and the 1,800-ft level—also imply storm winds arriving from the east or northeast. This suggests that the strongest storm winds during the highstands accompanying deposition of units AB and C, and the lowstands during deposition of unit A, were created by counter-clockwise-moving low-pressure centers that migrated along paths south of Searles Valley, probably reflecting the positions of the jet stream during those periods. However, the placement of these two unit A bars in the basin, and the orientations of their crests, may also reflect a time when the synoptic weather patterns were unlike those that prevailed during deposition of any of the younger units.

The lake-water circulation patterns characterizing the period when Searles Lake was relatively low and depositing

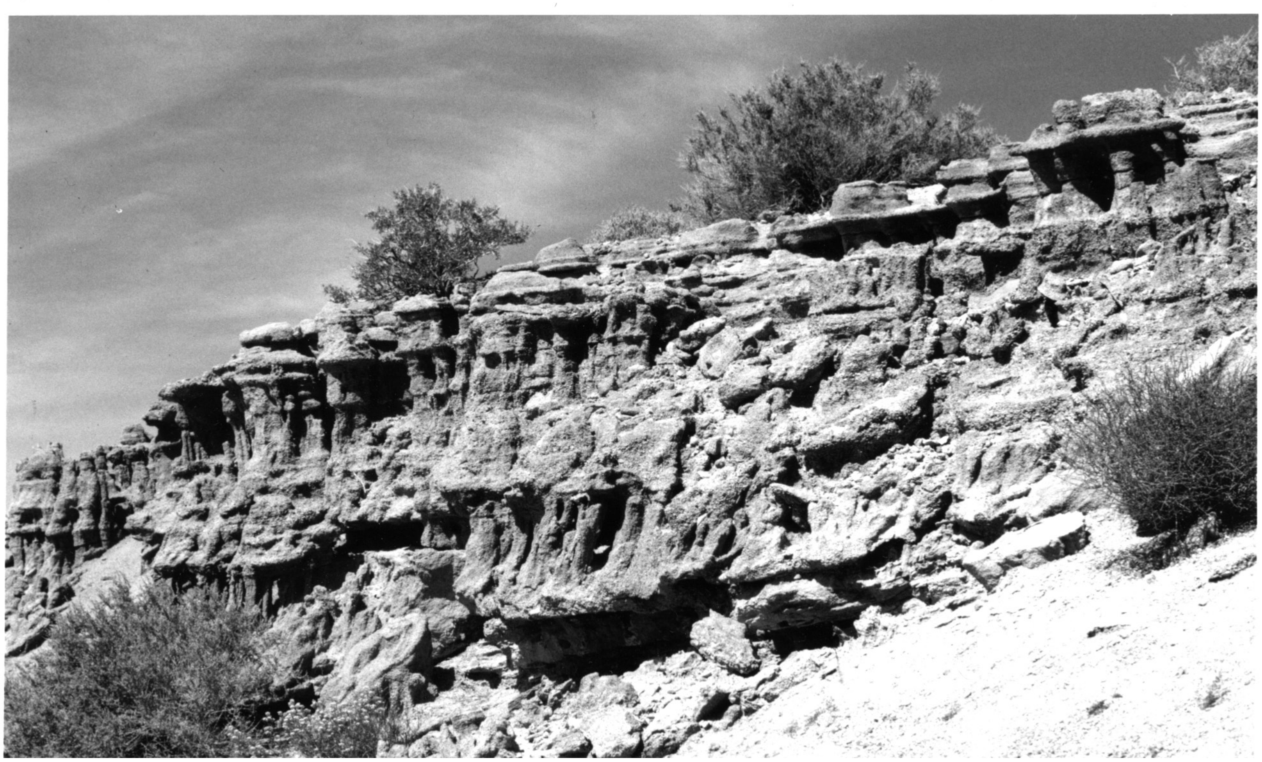


Figure 37. Defluidization structures (see text) preserved in outcrops of unit AB (location: pl. 2*A*, sec. C3-r). Tube-shaped vertical defluidization structures are mostly 20 to 30 cm high and 3 to 6 cm wide.

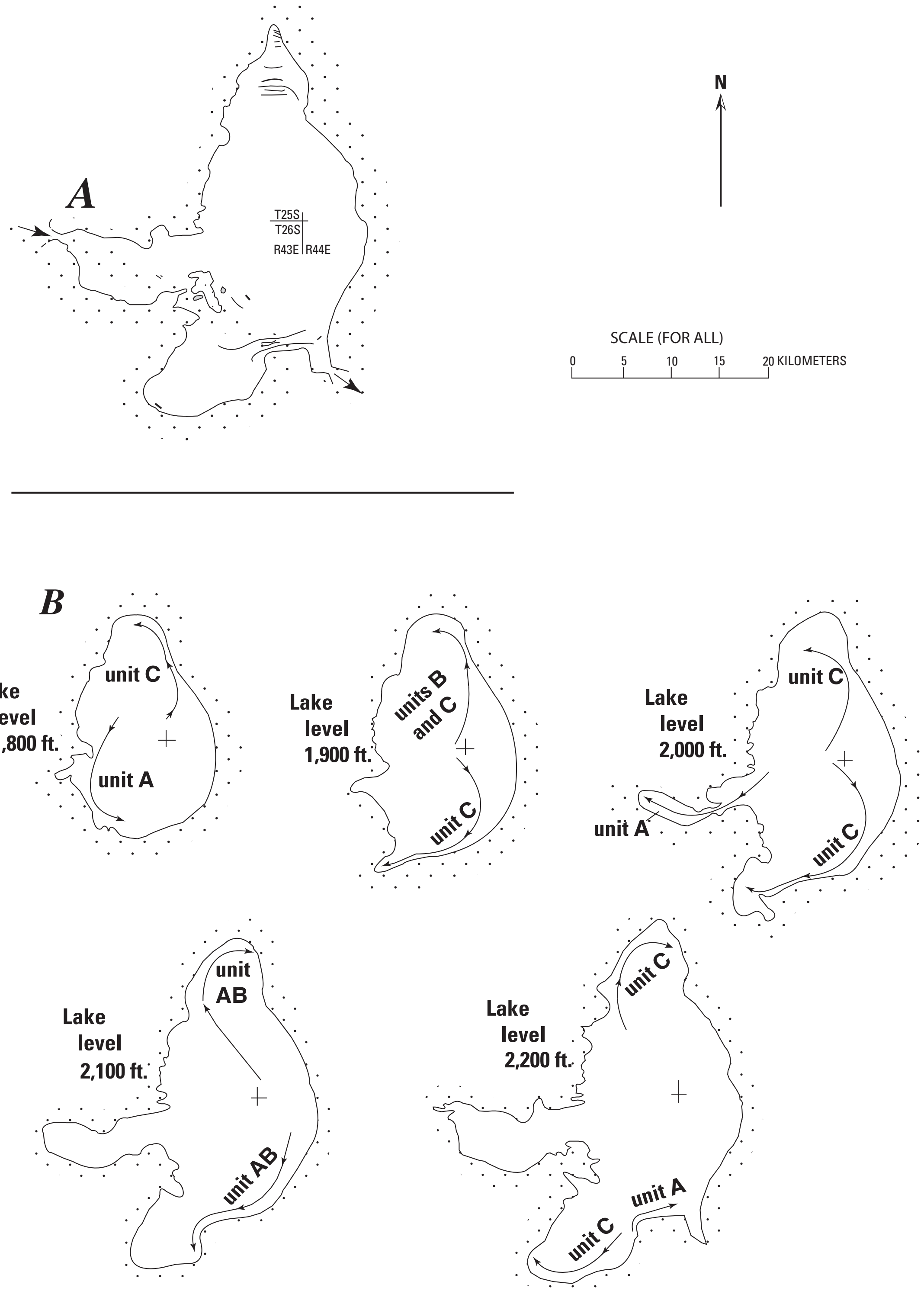


Figure 38. Outlines of Searles Lake and patterns of bar-forming currents at various lake levels. *A*, Extent of Searles Lake when its surface stood at its approximate maximum elevation of 2,280 ft or 696 m (stippled areas were above lake level) and the positions and shapes of major lacustrine bars (short curving lines) within the basin. Arrows show sites of inflow from China Lake and overflow into Panamint Valley. Reference cross in central part of lake shows intersection of boundaries separating T. 25 S. from T. 26 S., and R. 43 E. from R. 44 E. *B*, Outlines of Searles Lake at various lower levels, showing inferred current directions that constructed nearshore bars near each level; current directions determined from the lithologies of rock fragments and their bedrock sources. Note that a particular level (and its associated current pattern) may have been present at several different times; units of the Searles Lake Formation represented by lacustrine bars formed in each current pattern are indicated.

units B and C near the 2,000-ft, 1,900-ft, and 1,800-ft levels indicate that storm winds came from a westerly direction, eroding material from the Slate Range fans and transporting it north to northwest, and eroding material from the Lava Mountains and moving it southwest. Storm winds from the west suggest low-pressure zones that characteristically passed north of this area—which is the norm today.

Reconstructed History of Searles Lake

A major goal of this study is to reconstruct the history of Searles Lake over as many years as are recorded by lacustrine-sediment outcrops. Periods of expanded lakes are inferred from lacustrine sediments or tufas that can be traced laterally to high elevations on the valley sides, with the highest elevation, reliably correlated outcrop being used as the criterion of maximum lake depth during that period. Periods of lake contraction are inferred from alluvial sediments that can be traced to low levels in the valley. Where such layers can be reasonably correlated with subsurface saline layers, the shallower depths of those lakes can be approximated from the salinities implied by the mineralogy of their saline layers (Smith, 1979, p. 108-112).

Study of the accompanying geologic maps (pls. 1- 4) provides a first basis for reconstructing the changes in the depth of water during the time the Searles Lake Formation was being deposited. The highest elevation exposures of lacustrine deposits of each unit or subunit are listed in table 9, as are examples of the lowest elevation outcrops of interbedded alluvial units or subunits. The uppermost or lowermost elevations of outcrops of the same unit or correlative subunit were determined on each map that included exposures of them; the common similarities in the uppermost or lowermost elevations derived from two or more plates show that the tabulated elevations are unlikely to be the result of miscorrelation or misplotting. However, 20- to 30-ft (6 to 9 m) differences between elevations are not considered significant because (1) every outcrop has undergone some erosion, (2) interpolation between 40-ft contours can introduce this much error, and (3) the geologic contacts in areas of closely grouped contours can be misplotted by that much.

These outcrop elevations, when combined with data indicating the subsurface distribution of saline layers (Smith, 1979, fig. 41, pl. 2B) lead to a first approximation of the history of Searles Lake during deposition of the Searles Lake Formation (figs. 39*A* and 40*A*). Units and subunits of outcropping deposits assigned to the Searles Lake Formation are indicated in those figures, as are the named subsurface saline and mud layers. For units A, AB, BC, and C, supplemental data were derived from subsurface information on the chemistry and mineralogy of correlative units, and these are plotted in figures 39*B* and 40*B*. Combining these data leads to my interpretation of Searles Lake's history during the period between 35 ka and the present (fig. 39*C*) and the period between 170 ka and 30 ka (fig. 40*C*). The reasoning behind each of these interpretations is outlined below; more specific documentation of the rationale followed is presented in appendix 3. The diagram representing the younger of these two periods is discussed first because more information is available on these deposits, which allows us to test the rationale used to add detail to the history of the older deposits.

Units AB to D

Highstands of Searles Lake during deposition of units AB through D are plotted in figure 39*A*, solely on the basis of the highest elevations at which lacustrine sediments of each unit or subunit have been mapped (table 9). The lowstand lake level represented by unit BC is determined from the lowest elevation of alluvial deposits of that unit (table 9); the other lowstands are based on the presence and mineralogy of correlative subsurface saline layers. Monomineralic salt beds are assumed to have precipitated from lakes having about 13 percent salinity, implying an estimated lake depth of 130 ft (40 m) above the present deepest levels of those saline horizons (Smith, 1979, fig. 32). Multimineralic (but predesiccation) assemblages are assumed to be products of about 25 percent salinity, implying a depth of 65 ft (20 m). Desiccation assemblages indicate 35 percent salinity, implying depths of 0 to 40 ft (0 to 12 m). Salinity and lake-depth data, and depths to saline layers, are from Smith (1979, p. 1, figs. 7, 22, 26, and 32).

Subunits of units B and C that are dominated by fine-grained, deep-water lithologies were conservatively assumed during construction of figure 39*A* to represent lake-surface levels that were only about 50 ft (15 m) above the highest outcrop levels, but always with the understanding that the lake water could have been deeper. Units and subunits composed mostly of lacustrine gravel or sand were assumed to represent lake surfaces that were 10 ft (3 m) or less above the highest outcrop elevations.

Every deep-water segment of the lake-level curve plotted for unit B (fig. 39*A*) is alternatively plotted (dashed lines) up to the level of the spillway because of the abundance of lacustrine gravels assigned to unit B that can be traced up to that level. These gravels, plus abundant coatings of nodose tufa above 2,200 ft, show that at least one, and possibly several, of those proposed highstands is correct. The subunit assignment of the highstands plotted at 2,280 ft elevation for unit B, however, cannot be documented on the basis of outcrop stratigraphy. The two highest stands plotted for unit C (fig. 39*A*) are based on the mapped extent of that unit in the Valley Wells Wash area (pl. 2*A*). There, nearly continuous exposures of unit C and several other lacustrine units allow their upper elevation limits to be determined more accurately than in any other part of the basin.

Modifications of the history represented by unit B, and confirmation of the history proposed for units BC and C, can be made on the basis of correlative subsurface data—the absence or presence (and character) of laminae, their mineralogy, the acid-insoluble and acid-soluble CaO content of the Parting Mud in the GS-16 core, and on the thin saline layer near the base of the Parting Mud in that core (fig. 36).

The values for CaO were the prime basis for modifying the lake history represented by unit B (fig. 39*C*), although the character and mineralogy of the laminae provide supportive secondary criteria. (Although the acid-insoluble data from the GS-16 core are not used in refining the history of unit B, they are plotted in figure 39*B*, with the scale reversed so that the inverse relation between the CaO and acid-insoluble percentages produce similar curves. In the Bottom Mud, discussed below, data points based on the CaO content are few, but points based on the acid-insoluble content are numerous, and thus they become an important criterion in refining the history of unit A.)

In plotting the part of the curve representing unit B (fig. 39*C*), the following assumptions were made: (1) The percentage of CaO was directly proportional to inflowing water volume, (2) the lowest CaO percentage (at about 14 ka) reflected the inflow needed to sustain a lake at the 1,690-ft level (see description of unit BC), (3) the highest percentage of CaO reflected the inflow volume needed to reach the lake's overflow level, and (4) evaporation rates remained constant so that all of the difference in lake volume between its lowstand ($7x10^9$ m^3) and its highstand ($87x10^9$ m^3) was created by changes in inflow volume that led to proportionate changes in the percentage of Ca-bearing carbonate minerals deposited at the core site. Conversion of water volume to lake level is based on Smith (1979, fig. 32). Inasmuch as these analyses represent average conditions during approximately 1-k.y. intervals, brief fluctuations during deposition of unit B are not recorded by these data. Units BC and C remain plotted primarily on the basis of the elevation data in table 9, although those data are compatible with the lithologic and chemical information (figs. 36 and 39*B*).

Using the interpolated age scale, these analytical data and the information presented in figure 36 suggest the following: (1) Between 24 ka and 22 ka, the lake responsible for unit B remained small and briefly almost dry at one point (GS-16 is one of only two of the 41 GS-series cores that contained halite or trona at this horizon in the Parting Mud; Haines, 1957). (2) During the period from about 22 ka until about 15.5 ka, the lake received fluctuating but ever-increasing inflows of Ca-bearing water. Between 22 and 19 ka, when inflow could only sustain intermediate-size lakes, the amounts of CaO were inadequate and introduced too infrequently to produce many aragonite layers, so only unlaminated to coarsely laminated sediments were deposited throughout the basin. From 19 ka to 15.5 ka, as inflow continued to increase, it introduced CaO at a greater rate and on a more consistent basis, so laminae were deposited more frequently. (3) Between about 15.5 ka and 13.5 ka, lake inflow was markedly lower, reducing the amounts of Ca-bearing minerals being precipitated, and only coarsely laminated beds were deposited. (4) Starting at about 13.5 ka, concentrations of Ca-bearing minerals increased, showing that the volumes of inflowing water again increased; inflow reached a peak at about 12 ka, and a high inflow rate was maintained until almost 11 ka. During this period, finely laminated mud was frequently deposited in a stratified environment, as new influxes of water spread over the surface of the saline water body created during the previous shrinking stage. (5) By about 10.5 ka, the lake had shrunk to a level where the saline minerals borax and trona, which constitute the basal layer of the Upper Salt, were deposited.

Data obtained by F.M. Phillips and reported by Benson and others (1990, p. 270) may conflict with the history inferred here for the period between about 18.2 ka and 10.5 ka. Those data, based on the ^{18}O fluctuations in primary dolomite in the subsurface Parting Mud, are interpreted by Benson as follows: a shallow but slowly rising lake existed between 18.3 ka and 16.0 ka; it then rose to a highstand between 16.0 ka and 13.5 ka; a decline to moderately deep levels followed until 11.0 ka; and the lake rose briefly between 11.0 ka and 10.5 ka. Besides the uncertainties in the exact ages of these events, the source of the ^{18}O in the primary carbonate minerals must be carefully evaluated. Benson's interpretation assumes that isotopically light ^{18}O values indicate periods of expanding or relatively deep lakes (because fresh, isotopically light inflowing water was diluting the isotopically heavy brines of the earlier, shallower lake) and that isotopically heavy values indicate periods of shrinking or relatively shallow lakes (because inflow was too low to offset the evaporation that enriches water in the heavy isotope). In a saline, CO_3-rich lake, however, much of the inflow during periods of lake expansion entered a density-stratified lake; the CO_3-rich brine that resulted from the preexisting low stand constituted the lower layer, and the inflowing fresh water formed the upper layer. The CO_3 in the primary carbonate minerals precipitated during those periods may have largely—if not entirely—been the product of mixing along the chemocline, and their ^{18}O values may reflect the isotopic composition of the CO_3 in the older, underlying body of water rather than the average isotopic composition—and depth—of a homogeneous lake. Thus, while such isotopic data may accurately reflect periods of shrinking lakes, when there was little or no stratification, they are likely to incorrectly reflect periods—or depths—of expanding lakes, which is what characterized Searles Lake during much of the time the Parting Mud was being deposited (fig. 36).

The two expansions of Searles Lake between 13.5 ka and 10.5 ka, plotted in figure 39*C*, also conflict with data derived from cosmogenic ^3He in olivine crystals from basalt that constitutes the floor of the abandoned channel formerly connecting Owens Lake and China Lake, both upstream from Searles Valley (Cerling, 1990, p. 155). Those data indicate the age of the last streamflow capable of exposing fresh rock along the channel surface to be 15.5 ka (or 16.7 ka, depending on the calculation method used). This agrees well with the age of the highstand inferred by this study to have ended at 15.5 ka (fig. 39*C*), but not with the later expansions proposed here. Possibly, the subsequent episodes of Searles Lake expansion, between 13.5 ka and 10.5 ka, were too short or insufficiently intense to rescour the previously well polished and—even now—unweathered channel in the area studied by Cerling (1990).

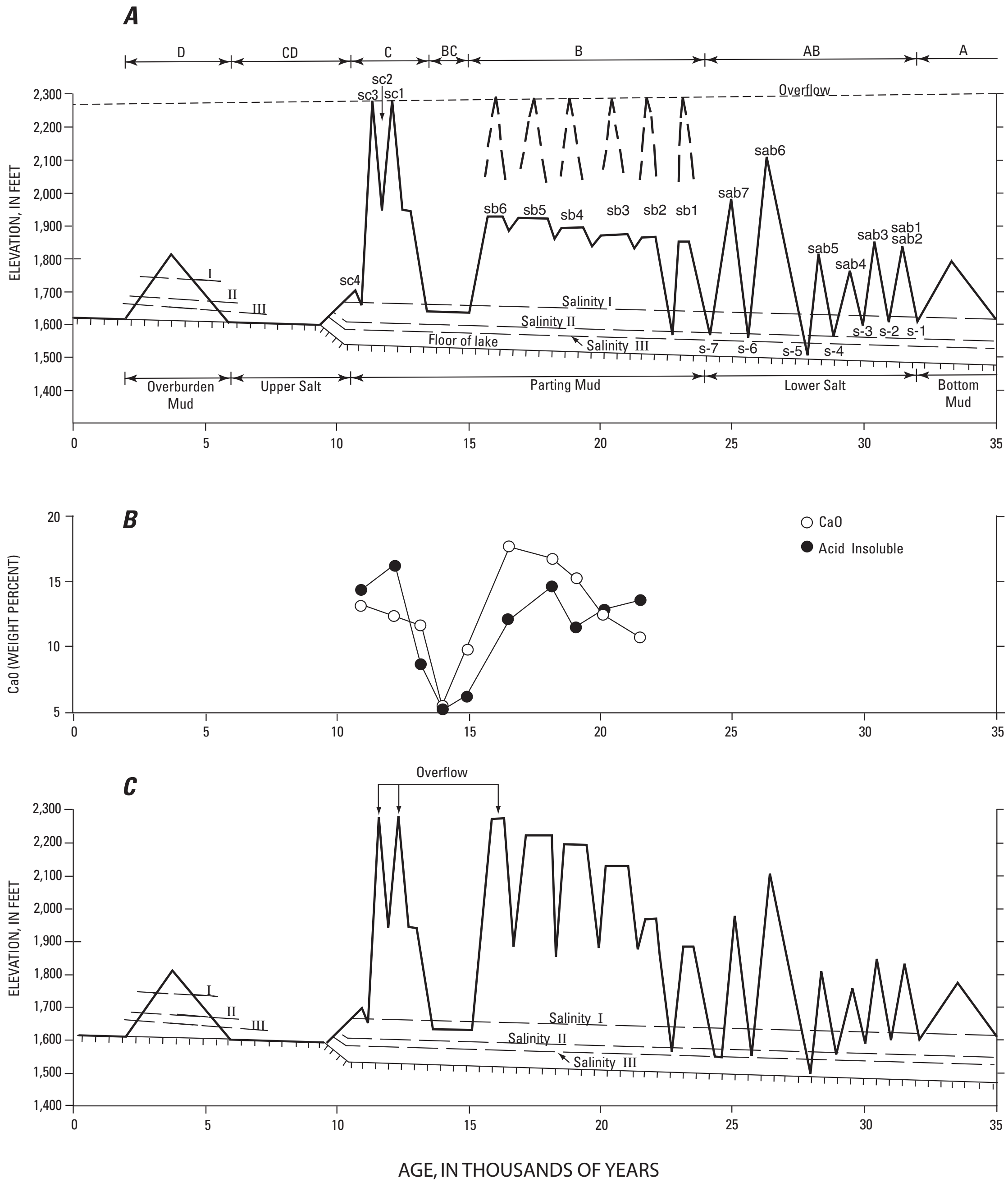


Figure 39. Inferred lake-level history of Searles Lake from 35 ka to the present. *A*, History of lake fluctuations (heavy lines) based on outcrop geology and subsurface salt beds. Age spans of outcrop units of Searles Lake Formation shown at top of diagram; selected subunits indicated immediately above solid lake-level line. Age spans of correlative, informally named subsurface units (table 3; Smith, 1979) shown near base of diagram; selected thinner subsurface units (salt beds) shown immediately below lake-level line. Plotted ages are linear interpolations between ages of subsurface-unit boundaries supplemented by dated samples from outcrops. Elevations of high-level stages based on data of table 9 (solid heavy line) and other data (dashed heavy lines, see text); elevations of low-level stages based on mineralogy of subsurface salines (Smith, 1979, p. 86-91, table 4; this report, fig. 36) and on lowest elevations of alluvial units (table 9). Short-dashed line shows elevation of overflow channel into Panamint Valley. Long-dashed, subhorizontal lines represent lake-surface elevations at three salinity levels: salinity I (near 13 weight percent) would permit winter crystallization of monomineralic suites, salinity II (25 percent) would permit multimineralic (but pre-desiccation) suites, and salinity III (35 percent) represents saturation or desiccation (see text). Elevation of floor of lake shown by hachured line. Slopes of bottom and salinity lines assume constant deposition rate (except during deposition of Upper Salt and Overburden Mud). *B*, Weight percentages of CaO and acid-insoluble material from figure 36; note that acid-insoluble scale is inverted. *C*, Levels of Searles Lake inferred from combining data in *A, B,* and selected other sources (see appendix 3).

Deposits of unit CD can be traced to the edge of now-dry Searles Lake, and although there is no subsurface evidence of subaerial deposition on the floor of the lake after crystallization of the Upper Salt, it is unlikely that clastic or salt sedimentation at that level ceased entirely. The depth and age of the lake responsible for the unit overlying the Upper Salt, unit D (fig. 39*C*), are based on data in table 9 and the ^{14}C date of 3.5 ka on wood that was recovered 2.4 m below the surface of Searles (dry) Lake, about a third of the distance between the surface and the base of the Overburden Mud. The ages of the beginning and end of that cycle are plotted at about 6 ka and 2 ka. The age of the beginning of this readvance (6 ka) is a very inexact estimate based on the thickness of sediment underlying the dated wood sample in the Overburden Mud (unit D) (Stuiver and Smith, 1979, p. 73); the estimated age of redesiccation (2 ka) is based on an assumed correlation with the age of the close of the Dechambeau Ranch highstand in Mono Lake (Stine, 1990, fig. 3), and data from Owens Lake cited by Smith (1976, p. 99, footnote 2). These ages, however, conflict with evidence from Owens Lake and Little Lake (50 km south of Owens Lake), which indicate the time of the last overflow from Owens Lake was prior to 5 ka (Smith and others, 1997, p. 148; Mehringer and Sheppard, 1978).

The suggested boundaries between the correlative outcrop units are not plotted in figure 39*C* because the mechanics of lacustrine deposition during transgressive and regressive stages result in the actual ages of the contacts between outcropping units differing slightly from one elevation to the next.

Unit A

Age control within the outcropping section of sediments mapped as unit A is not as good as for younger units (fig. 40). With two exceptions, the ^{14}C ages on outcrop material from unit A (table 5) appear to be too young, which may be a result of contamination by the waters of subsequent lakes, exposure to the atmosphere, or unknown complications. Three of the six U-series ages determined on samples from that unit appear much too young and three are possibly correct, but two samples from the same bed differ by 23 k.y. (Garcia and others, 1993). Three other samples were submitted for U-series dating at an earlier date. Two were samples of nodose(?) tufa that gave similar and reasonable-appearing dates (average, 21.6 ka) by U-series and Pr-series methods; one was a sample of marl from unit A that gave a date inconsistent with its stratigraphic position.

In this study, the age range represented by outcrops of unit A is based on the estimated ages of upper and lower contacts of the subsurface Bottom Mud (Smith, 1979, p. 16-17, 49, 79, 108-112, figs. 6, 31, 32, 41, and pl. 2; Stuiver and Smith, 1979, p. 73-75; Peng and others; 1978, Bischoff and others, 1985). Age control on the top of this subsurface correlative is good; both ^{14}C and U-series ages indicate its age to be near 32 ka. However, a 20-k.y. difference in the age of the basal contact of the Bottom Mud arises from two approaches to the question. Depositional-rate extrapolation suggests a 130-ka age (Smith, 1979, p. 75), and the U-series age of the one subsurface sample of a saline mineral layer closest to that horizon also indicates its age to be near 130 ka (Bischoff and others, 1985, table 1, sample 7). However, by disregarding that single radiometric-age point and using the remarkably linear age-depth trend set by seven other U-series dates above and below this contact (Bischoff and others, 1985, fig. 2, samples 2 through 6, 8, and 9), the age of the contact appears to be nearer 150 ka. This age of lake-level change, which is used in this paper, also conforms with that estimated from the chloride-budget studies of Searles Lake by Jannik (1989).

There are also significant discrepancies between some of the U-series and ^{14}C ages from within the Bottom Mud (fig. 40*A*). About 3 m below the upper contact, a ^{14}C age of 46.3 ka on organic carbon differs from a U-series age of 58.4 ka from gaylussite crystals at about the same horizon, and two U-series ages from the uppermost part of the Mixed Layer differ by 26 k.y. Furthermore, many of the U-series ages differ from the linearly interpolated ages plotted below the base of figure 40*A*, suggesting that the assumption of uniform depositional rates may misrepresent the ages of various events during this part of the lake's history by 10 to 30 k.y. Therefore, a second time scale is plotted just above the base of figure 40*A* that indicates the approximate ages of various horizons according to the U-series dates. (It is constructed by using the seven linear-plotting U-series dates as follows: the two closely spaced dated samples that bracket the 60-ka age were used to establish that point, and linear interpolation between 32 ka and 60 ka and between 60 ka and 150 ka was used to establish the remaining points.) This U-series scale, however, requires the sedimentation rate of marl during the period between 60 ka and 32 ka to have been about half the rate of earlier deposition as well as of the rate determined, using ^{14}C dates, for the younger Parting Mud (Smith, 1979, p. 76-77). These inconsistencies illustrate why reservations must always accompany ages determined on the basis of a sedimentation rate calculated using another part of a core. For simplicity in discussing the lake-level variations reconstructed by this study, however, the time scale based on the assumption of uniform depositional rate—what could be considered a nominal age—is used in subsequent discussions because the inconsistencies between the existing radiometric dates make it difficult to devise a more assuredly accurate method of plotting the data.

Some of the largest masses of lithoid tufa near The Pinnacles are stratigraphically at the base of subunit sa1, implying that a favorable period for the growth of lithoid tufa existed near the beginning of deposition of unit A. Plotting the level of the lake responsible for the middle part of that subunit at the overflow level is also justified by the massive lithoid tufa deposits found at and just below the high shoreline, as well as the massive deposits of lacustrine gravel assigned to unit A that were deposited just below that shoreline. This inference of an overflowing lake in Searles Valley during deposition of subunit sa1 is also supported by evidence of chloride loss from Searles Valley to Panamint Valley at this time (described below). The highest elevation deposits mapped as subunit sa3 lie at 1,920 ft (table 9), but overflow levels are also postulated

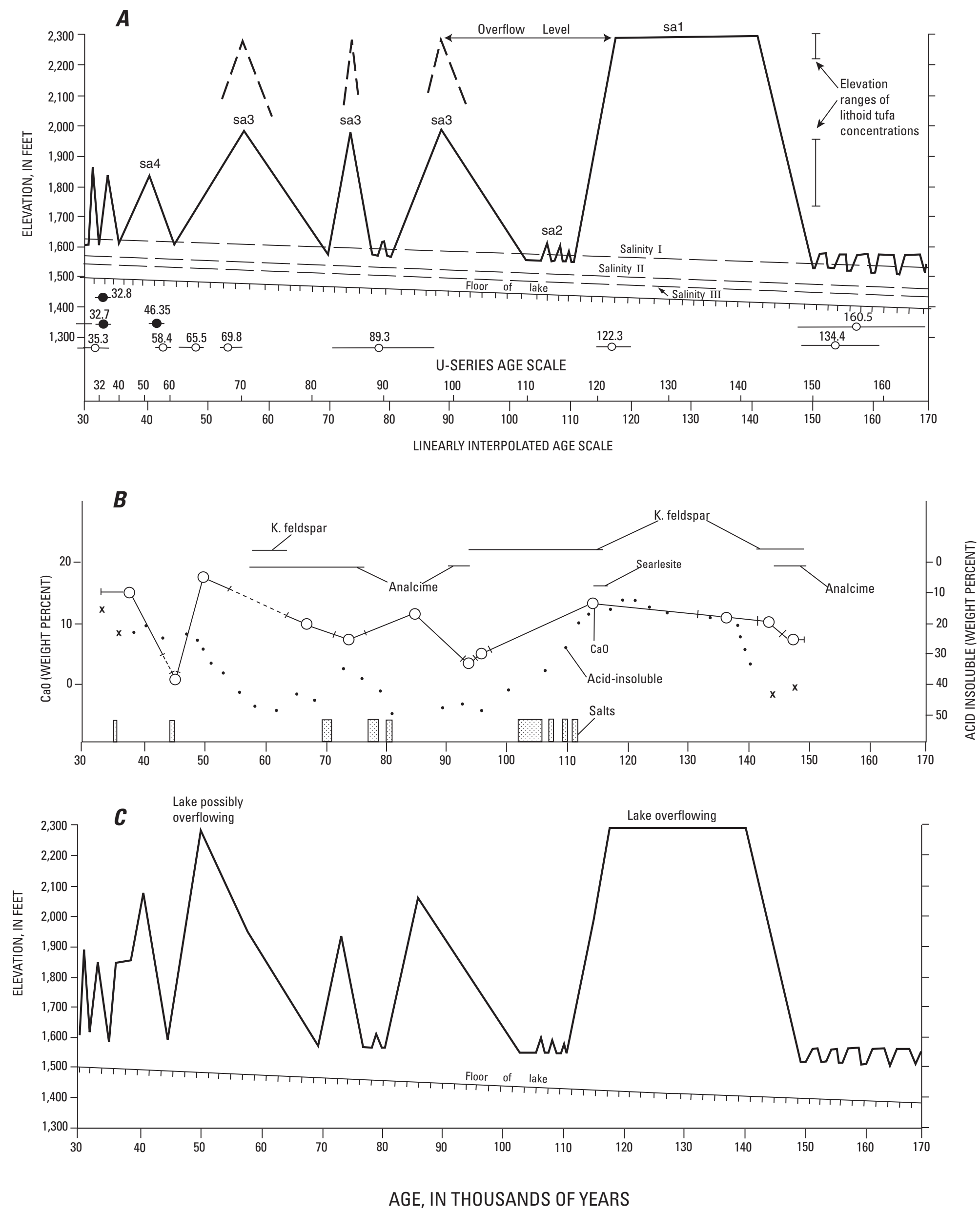


Figure 40. Inferred lake-level history of Searles Lake from 170 ka to 30 ka. *A*, History of lake fluctuations (heavy lines) based on outcrop geology and subsurface salt beds. Subunits of outcropping unit A of the Searles Lake Formation, which extends from 150 ka to 32 ka, are labeled above lake-level line; lake history before 150 ka based on lithologies of the subsurface Mixed Layer. Elevations of high-level stages based on data of table 9 (solid heavy line) and other data (dashed heavy lines). Radiometric ages plotted near base of diagram (bars show experimental uncertainty); ^{14}C ages (dots) are from Stuiver and Smith (1979, fig. 30), and U-series ages (circles) are from Bischoff and others (1985, table 1). Age scale plotted below bottom line of diagram *A* is interpolated linearly from the ages of the base (150 ka) and top (32 ka) of the Bottom Mud (this scale also used in parts *B* and *C*); age scale plotted above bottom line of diagram *A* based on U-series dates (see text). Overflow level is elevation of spillover channel into Panamint Valley. Dashed, subhorizontal lines represent lake-surface elevations at three salinity levels: salinity I (near 13 weight percent) would permit winter crystallization of monomineralic suites, salinity II (25 percent) would permit multimineralic (but pre-desiccation) suites, and salinity III (35 percent) represents saturation or desiccation (see text). Elevation of floor of lake shown by hachured line. *B*, Compositional data for Bottom Mud. Age ranges of diagenetic minerals that suggest higher lake salinities (K-feldspar, analcime, and searlesite), acid-insoluble content (moving 5-point averages shown: small dots, accurate data; x's, less accurate data), and ages of monomineralic salt beds (stippled vertical bars) are from cores 254 and L-30 (Smith, 1979, figs. 6 and 41, plate 2B); CaO analyses (circles) are from core KM-3 (Smith and others, 1983, pl. 2). Note that scale for acid insoluble is inverted. *C*, Lake history as inferred from data in parts *A* and *B* and selected other sources (see appendix 3).

(fig. 40*A*) for the lakes responsible for subunit sa3. These are thought permissible because field notes record observations of lacustrine gravels at levels between 2,000 ft and 2,280 ft elevation, mapped as part of unit A, that rested on alluvial gravels having fossil soils similar to those developed at lower elevations on subunit sa2, but not similar to those on gravels of the Christmas Canyon Formation and older gravels unit. The upper level plotted for the lake responsible for subunit sa4 is based on the elevation of the gravels that can be traced to the surface of the prominent bar northwest of The Pinnacles that is composed of that unit (pl. 4).

The lacustrine retreat and alluvial readvance during deposition of subunit sa2 is plotted within the interval 112 to 102 ka (fig. 40*A*), because that is the interpolated age of the thickest of five zones of monomineralic salts in the Bottom Mud as represented by core 254 (Smith, 1979, pl. 2; shown here in fig. 40*B*). The placement of alluvial subunit sa2 is also supported by its position in the lower third of good exposures of unit A (secs. I32-r and K24-p,q, pl. 4). The other four low-level stands in unit A (fig. 40*A*), representing the other four zones of monomineralic salts in cores 254 and L-30, are plotted at the intervals extending from 81 to 77 ka, 70 to 68 ka, 46 to 45 ka, and 36 to 35 ka; these layers also may have alluvial counterparts in the exposed record, but none were recognized. Sediments deposited in lakes having higher salinities and lower levels are placed within zones in the subsurface deposits containing diagenetic analcime, searlesite, and K-feldspar, which imply higher salinities (fig. 40*B*). Evidence described by Sheppard and Gude (1968, p. 33-36) suggests that diagenetic K-feldspar and searlesite are products of reactions with interstitial brines having higher salinities than those involved in the formation of diagenetic analcime and that all three minerals are indicative of elevated salinities. It is clear, however, that the ages inferred for these shallow- to intermediate-level stands of Searles Lake during deposition of unit A (fig. 40*C*) must be used cautiously, because they have large uncertainties.

The lack of short-period variations in the lake history plotted for subunit sa1 contrasts with that plotted for younger units. This resulted in part from differences in the preservation and exposure of the older and younger records. However, if Searles Lake did stand at overflow levels during most of the period subunit sa1 was being deposited, relatively few fluctuations would appear in even the most accurate curve depicting that part of its history. This is because when the overflow from Searles Lake was voluminous, smaller magnitude climatic fluctuations like those revealed by the lacustrine sediments assigned to younger units in the Searles Lake Formation would have been expressed downstream, by the lakes in Panamint and Death Valleys, rather than in Searles Valley (fig. 41; note history plotted between 1.6 Ma and 1.2 Ma).

A large lake in Panamint Valley requires inflow from Searles Valley, because Panamint Valley's drainage area is inadequate to collect the necessary amounts of water (R. Smith, 1978). Table 10 lists the approximate areas and volumes of water contained by the five interconnected lakes in the Owens River system during their Pleistocene maxima. The volume of water required to fill Panamint Valley alone, similar to the volume required to fill Owens, China, and Searles Lakes together, indicates that runoff intensities during times when Panamint Valley contained a large lake were much greater and more persistent than at any subsequent time. Data compiled by Jannik (1989, fig. 38) on the chloride budgets in Searles and Panamint Valleys, supplemented by ^{36}Cl and other radiometric data from both valleys, indicate a period of major chloride transport into Panamint Valley between 150 ka and 120 ka. Smith and Street-Perrott (1983, table 10-2) estimate the Owens River runoff volume needed to fill Panamint Valley was about 6.5 times that of present runoff, assuming that a temperature decrease of 5°C accompanied the precipitation increase.

A temperature decrease of about 5°C during wetter periods of the late Pleistocene is indicated by many types of data, but the evidence of Winograd and others (1988, table 2, fig. 4) from the Death Valley area indicates that a relative warming period started about 150 ka. This requires the overflow period of Searles Lake, plotted between 140 ka and 118 ka (fig. 40*C*), to have coincided with the interglacial period as proposed by those authors. If the atmospheric temperatures during that overflow period were about the same as today's temperatures, rather than 5°C cooler, regional runoff volumes nearly nine times those of the present would have been required to fill and maintain a lake in Panamint Valley and all of the lakes upstream from it (Smith and Street-Perrott, 1983, table 10-2). Possible support for a modern-temperature evaporation rate comes from the results of computer modeling of Lake Lahontan's (Nevada) response to changes in inflow (Benson and Paillet, 1989, fig. 8); computer-simulated filling of that lake to its highest late Pleistocene level required a ninefold increase in inflow.

Reconstructed Paleohydrology of Lakes in the Owens River System

Much of the justification for mapping lacustrine and other late Cenozoic sediments in Searles Valley is based on the need to know more details of the regional hydrologic and climatic changes. Studies of Pleistocene lakes in other western United States basins, largely oriented toward the same goals, have been carried out over more than a century. Milestone studies prior to 1980 are noted by Smith and Street-Perrott (1983, p. 190), and subsequent studies are summarized by Benson and Thompson (1987b, p. 244-251) and Benson and others (1990). Most of the studies made over the past few decades have had the advantage of radiometric and other quantitative methods of determining the ages of lacustrine deposits. However, precision in dating many deposits has proved elusive for a variety of reasons that are summarized earlier in this paper. Nonetheless, though some of the dates on outcrop material presented in this report are also considered unreliable (table 5, dates enclosed by parentheses), the overall consistency of dates from outcrop units less than 30 ka in age, the variety of materials dated, and the stratigraphic correlation with better dated subsurface sediments combine to support the approximate ages assigned here.

In addition to the dating problems noted above, reconstruction of a succession of hydrologic environments from a lacustrine history requires that the response of rivers and lakes to changes in each of several aspects of climate be quantified. Many studies of these aspects have been made; the earliest was probably Halley (1715), but more modern studies include those of Langbein (1961), Snyder and Langbein (1962), Schumm (1965), Benson (1981, 1986), Smith and Street-Perrott (1983), Benson and Paillet (1989), Benson and others (1990), and Smith (1991b). Most of them acknowledge the ambiguities among several elements of climate that could have affected runoff volumes and lake levels. These include changes in (1) the total amount and seasonal distribution of precipitation, (2) air and lake-surface-water temperatures, (3) relative humidity, (4) cloudiness, (5) windiness, and (6) vegetation cover. Almost none of these are accurately recorded in the geologic record, but they all influence the percentage of precipitation that became runoff and the inflow-evaporation ratios of lakes. Probable changes in evaporation rates are small when compared with the possible changes in inflow volumes (Smith, 1991b, p. 36). For some geologic purposes, records of the ages and magnitudes of variations in runoff volumes are of more value than reconstructions of the climatic balances that controlled them, because runoff-volume data can be applied directly to studies of geologically important processes such as stream sizes and velocities, flood frequencies, and sedimentation and erosion rates.

Interrelations between adjoining subbasins that first contribute to (or receive water from) an adjacent basin are necessary concepts when correlating lake histories (Benson and Thompson, 1987b, p. 244-247, figs. 4-7; Benson and others, 1990, p. 39). Both Lake Bonneville and Lake Lahontan, the two largest Pleistocene lakes in the Great Basin, are each composed of a series of adjoining subbasins. Many smaller Pleistocene lakes in the Great Basin also are thought to have overflowed into adjacent basins (Snyder and others, 1964). Searles Lake represents a variation of those relations in that it was third in a series of as many as five sequential basins fed primarily by the Owens River, only two of which (Searles and China) ever merged to form a single lake. The

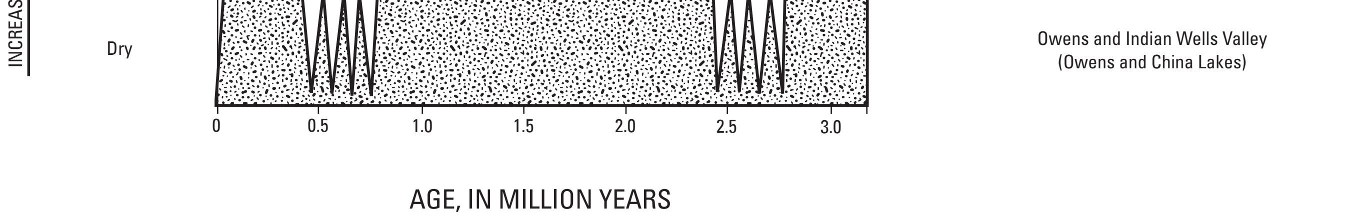


Figure 41. Diagrammatic representation of climatic regimes in the region of the Owens River system from 3.2 Ma to the present (modified from Smith, 1984, fig. 4). The position of Searles Lake in the middle of a chain of lake basins means that the degree of detail in its record of climatic variations is itself very variable. During long periods of dominantly wet climates, Searles Lake would generally remain full and overflowing, spilling its excess to downstream lakes (Panamint and perhaps Manly). During long periods of dominantly dry climates (like the present), Searles Lake would generally receive no input from overflowing upstream lakes (Owens and China) and remain dry or highly saline. Only during periods of dominantly intermediate climates, when it generally received input from upstream but rarely reached overflow level itself, would Searles Lake produce a detailed record of the many shorter, less extreme climatic fluctuations. The major fluctuations are plotted as 400,000 years long, the approximate frequency of the astronomical cycle suggested by Smith (1984) as the most important control of the climates that determined Searles Lake's history. The minor cyclic fluctuations are plotted as 100,000 years long, the longest of three periodicities well represented in the marine record of high-latitude glaciation. Theoretically, the 400,000-yr and 100,000-yr (and shorter) periodicities are astronomically induced by cyclic variations in the Earth's tilt and orbit relative to the Sun.

Table 10. Approximate areas and volumes of historic and Pleistocene-maxima lakes of the Owens River system.

Lake name	Historic Area (km²)	Historic Volume (10^9 m³)	Pleistocene maximum Area (km²)	Pleistocene maximum Volume (10^9 m³)
Mono	200[1]	3.77	440	63.6
Owens	285[2]	2.95	695	14.3
China	0[3]	0	995[4] (China and Searles)	79.4[4] (China and Searles)
Searles	0[3]	0		
Panamint	0[3]	0	710	105.2

[1]Scholl and others (1967, p. 584, fig. 4); value for 1964.

[2]Gale (1914); data are for level of 1872, before irrigation and construction of Los Angeles Aqueduct.

[3]Normally dry most of year. Approximate areas of playas (km²): China, 20; Searles, 100; north Panamint, 18; south Panamint, 46.

[4]Searles and China Lakes coalesced into one water body at highest stands.

Owens River chain also received water from the Mono Lake basin at times.

During periods that were on average dry, Searles Lake had the lowest potential of any of the five basins for significant runoff from its own drainage area (table 11), which includes no mountains higher than 6,562 ft (2,000 m). At such times, the impact of brief periods of climate change on the basin containing Searles Lake would have differed from the impact on lakes in basins bordered by high mountain ranges. Owens Lake, and China Lake at times, probably began enlarging very shortly after the first increase in regional precipitation produced additional inflow from the adjoining high-elevation slopes of the Sierra Nevada. Downstream Panamint Lake, with mountains ranging up to 11,048 ft (3,368 m) on the east and 8,839 ft (2,694 m) on the west, might have received some increase in local inflow during transitions to a wetter climate, but calculations show that lakes as large as those recorded by its highest shorelines and sediments required inflow from Searles Lake and its upstream drainages (R. Smith, 1978). Searles Lake's levels responded most sensitively to climate change during climatic regimes that on average were intermediate in intensity, compared with the present dry regime (when Searles Lake is almost permanently dry) or the most extreme wet regimes (when either Panamint or Death Valley contained the terminal lake). The schematic diagram of the history of lakes in Searles Valley since 3.2 Ma (fig. 41) illustrates the effect of this hydrologic setting on its record of past climates.

What this setting means is that when the Owens River supplied the water volume it carries today, no water from that system could have reached Searles Valley until a fairly substantial increase in regional runoff occurred. Smith and Street-Perrott (1983, table 10-2) calculate, for example, that assuming no change in temperature and no contribution from other streams, Owens River flow would have had to more than double relative to its modern (1872) flow for Owens Lake to fill and begin to overflow. Historically, even an abnormally wet year (1968-69) produced flow in the Owens River that did not equal the amount required to meet this average-flow-volume requirement. For China and Searles Lakes to also fill, river flow would have had to increase sixfold. Lake-surface temperature decreases of 5°C would have decreased evaporation and reduced these increased-flow requirements by about 25 percent, but no reasonable temperature reduction could have eliminated the need for increased inflow for Owens River water to reach Searles Lake. In other words, for Owens River flow to have caused a perennial lake to develop in Searles Valley, regional runoff would have had to increase several-fold over present runoff, meaning that any record of perennial-lake sedimentation in Searles Valley documents a climatic scenario that most workers would consider to have already reached a pluvial-like level.

The lacustrine history recorded by the deposits of the Searles Lake Formation (figs. 39*C* and 40*C*) shows, therefore, that most of the past 150 k.y. have been characterized by a much wetter hydrologic environment and climate than now prevails. Unit A represents the wettest of these periods. During the 17-k.y. period between 140 ka and 118 ka (subunit sa1), a large and vigorously overflowing lake is interpreted to have occupied this valley. During subsequent periods, centered at the nominal ages of about 108, 79, 70, 45, and 35 ka, perennial lake sizes shrank to depths that allowed monomineralic salines to precipitate during cold periods (Smith, 1979, p. 16-18, pl. 2). Between these low stands, the lake stood at intermediate levels for periods as long as 25 k.y. Using the climatic labels of figure 41, the lake-level history represented by unit A indicates a climatic regime that varied from wet to intermediate but not to dry.

Lake fluctuations indicated by the stratigraphy of units AB through D of the Searles Lake Formation, however, imply more frequent climatic variations than during the deposition of unit A. Within a period of about 32 k.y. (fig. 39*C*), 15 lake expansions are separated by 15 contractions but only 3 desiccations. These represent complete cycles, on average, about every 2 k.y. More than 84 percent of this period represented intermediate hydrologic regimes in this drainage area; the only "dry" episodes centered on periods near 28 ka (which was probably very brief), 8 ka (which perhaps accounted for about 4.5 k.y.), and 1 ka. These are documented by subunit S-5 of the subsurface Lower Salt, the subsurface Upper Salt, and the presently dry surface of Searles Lake, respectively.

Figure 42 plots Searles Lake fluctuations over the past 150 k.y. in terms of required inflow volumes from the Owens River plus the small amounts from other streams that flowed directly into Owens, China, and Searles Lakes. This figure resembles the diagrams of Searles Lake levels (figs. 39*C* and 40*C*) but is more subdued. The reason for this is that, during periods when Searles Lake fluctuated, the evaporation losses from upstream Owens and China Lakes, estimated to be 0.89 and 1.02 m/yr, respectively (Smith and Street-Perrott, 1983, table 10-2), remained nearly constant because those lakes remained full. Thus, if Searles Lake was full but not overflowing, a reduction of about 56 percent in Owens River flow could cause Searles to desiccate—a 100 percent change in lake level that was caused by little more than 50 percent change in runoff.

Figure 42 also shows (1) that about 81 percent of the 150-k.y. period was characterized by runoff volumes between about 2.0 and 4.5 times present Owens River runoff (and thus intermediate in the terminology used in fig. 41), (2) that about 14 percent of the time those volumes exceeded 4.5 times present runoff (thus wet), and (3) that 4 percent of the time—which includes the present—flow fell below twice present volumes (thus dry). A case could be made that the four wet pulses at about 125, 85, 50, and 15 ka, which are about 40 k.y. apart, were possibly expressions of the Earth's 41-k.y. obliquity cycle, but the large uncertainties in the ages of deposits too old for ^{14}C dating makes this suggestion tenuous. What is not tenuous, however, is the evidence (fig. 42) that, except for the past 10 k.y., most of the preceding 150 k.y.—including the last interglacial period, which is usually considered to have been a relatively dry time—was characterized by flow volumes in the Owens River that were more than twice historic flow volumes. This conclusion is supported and broadened by the study of a core from Owens Lake by Smith and others (1997, p. 149), in an area much less arid than Searles Valley, which shows that in this watershed, and probably in a much larger area, the period since 5 ka has been more arid than any other period since sometime before 800 ka!

Considering again the entire 3.2-m.y. lacustrine record from Searles Lake (Smith and others, 1983, table 1), we see that during Pleistocene and late Pliocene time, only two periods represent times of nearly continuous desiccation and a lack of significant inflow. The first lasted from approximately 2.56 to 2.04 Ma (a period of about 0.52 m.y.) and the second from 0.57 to 0.31 Ma (0.26 m.y.), together accounting for about a quarter of that total 3.2-m.y. period. Since 0.31 Ma, however, the desiccations of Searles Lake that occurred at about 28 ka, and during the early and late Holocene, account for less than 3 percent of that period.

In this area, paleohydrologic trends during the past 3.2 m.y. were also caused by continuing uplift of the Sierra Nevada, which affected climates in the drainage areas of the Owens River and downstream lakes. The part of the Sierra Nevada just west of the Owens River's headwaters has been uplifted by nearly 1,000 m in the past 3 m.y. (Huber, 1981). At the outset of this period, air masses had capacities to transport almost 50 percent more moisture to areas east of the Sierra Nevada than they do now (Smith and others, 1983, p. 23), so that continuing uplift steadily intensified the rain shadow east of the range. Other lines of evidence support this trend; increasing percentages of chemical sediments in the lake deposits in Searles Valley are attributed to this encroaching aridity (Smith and others, 1983, p. 19), and isotopic studies of fluid inclusions in calcite veins in Death Valley reflect this uplift and increased blockage of precipitation (Winograd and others, 1985). It is significant, however, that the longest dry episode and the longest wet episode in the 3.2-m.y. record from Searles Lake were both in the earliest third of that period. Clearly, climatic variabilities have greatly exceeded any effects caused by geological changes in this area.

Table 11. Distribution of drainage-area elevations for five lake basins in Pleistocene Owens River system.

Elevation range (10^3 ft)	Drainage areas (km^2) Mono Lake	Owens Lake	China Lake	Searles Lake	Panamint Lake
14+		8			
13 to 14		512			
12 to 13	34	217			
11 to 12	93	247			1
10 to 11	217	388			2
9 to 10	264	394			16
8 to 9	435	476	3		26
7 to 8	1,320	862	256		145
6 to 7	956	896	131	3	396
5 to 6		1,300	373	21	632
4 to 5		1,698	399	158	717
3 to 4		1,424	1,432	352	823
2 to 3			417	637	1,004
1 to 2				461	810
Total	3,319	8,422	3,011	1,632	4,571

Comparison of the Owens River System with the Reconstructed Paleohydrologies of Other Areas in the Western United States

Correlation and comparison of the paleohydrologic history represented by the Searles Lake Formation with the histories of other areas shows several meaningful similarities and some differences. Some of the apparent differences may be caused simply by a lack of accurate age control, but many others appear to be real. Problems with age control for the period preceding 35 ka, the approximate older limit of the

^{14}C dating method, result from both smaller percentages of preserved deposits as outcrops and the difficulties in finding reliable dating materials and methods for these older deposits.

Even though some subbasin lakes may have coalesced as they approached their maximum sizes, problems arise when correlating the earlier histories of the individual basins, because they were inherently different if their individual hydrological settings were not similar. A study of the responses by Owens and Searles Lakes to major climate changes since 800 ka documents large differences in the timing of when those changes registered in each lake's sediments. The explanation for these timing differences is that Searles Lake lies in a much more arid region than Owens Lake, as measured by the amounts of precipitation that fall within their respective drainages. For example, when the climate changed from a relatively wet one, which allowed Owens Lake to contribute water to China and Searles Lakes, to one that was more arid, the overflow from Owens Lake would have decreased and eventually stopped. With a probable evaporation rate of >1 m/yr at Searles Lake (Smith and Street-Perrott, 1983, table 10-2), a few centuries with no inflow would have caused it to desiccate. At the same time, however, Owens Lake would probably still be full or almost so, depositing sediments indicative of a wet environment. Conversely, when the climate changed back from arid to wet, Owens Lake would have been the first to receive inflow from the Sierra Nevada and the first to expand, almost immediately depositing sediments indicative of a deeper lake and a wetter climate. During the time required for Owens Lake to fill and overflow into China Lake, and for that lake to also fill and overflow, Searles Lake would have remained a salt flat. Only when the flow into Searles Lake became voluminous enough to offset annual evaporation and end saline deposition did the sediments deposited in Searles Lake belatedly register a change of climate.

In this way, sediments deposited in the basin most remote from the main source of runoff were the first to record a period of decreasing runoff, and sediments deposited in the basin closest to the main source of runoff were the first to record a period of increasing runoff. The sedimentary records from Searles and Owens Lakes show that they followed this anticipated sequence, and that they required long delays before the same climatic change was recorded in the basin slower to respond. Considering that these staggered sedimentary responses reflected the same climate changes as recorded in successively connected basins fed by the same river, the very long delays seem to document some climate changes that were very gradual. The apparent delays in the Owens and Searles Lake records covering the past 800 k.y. ranged from 5 k.y. to 100 k.y., but only the delay that lasted from 10 ka to 5 ka lies within the period discussed by this study.

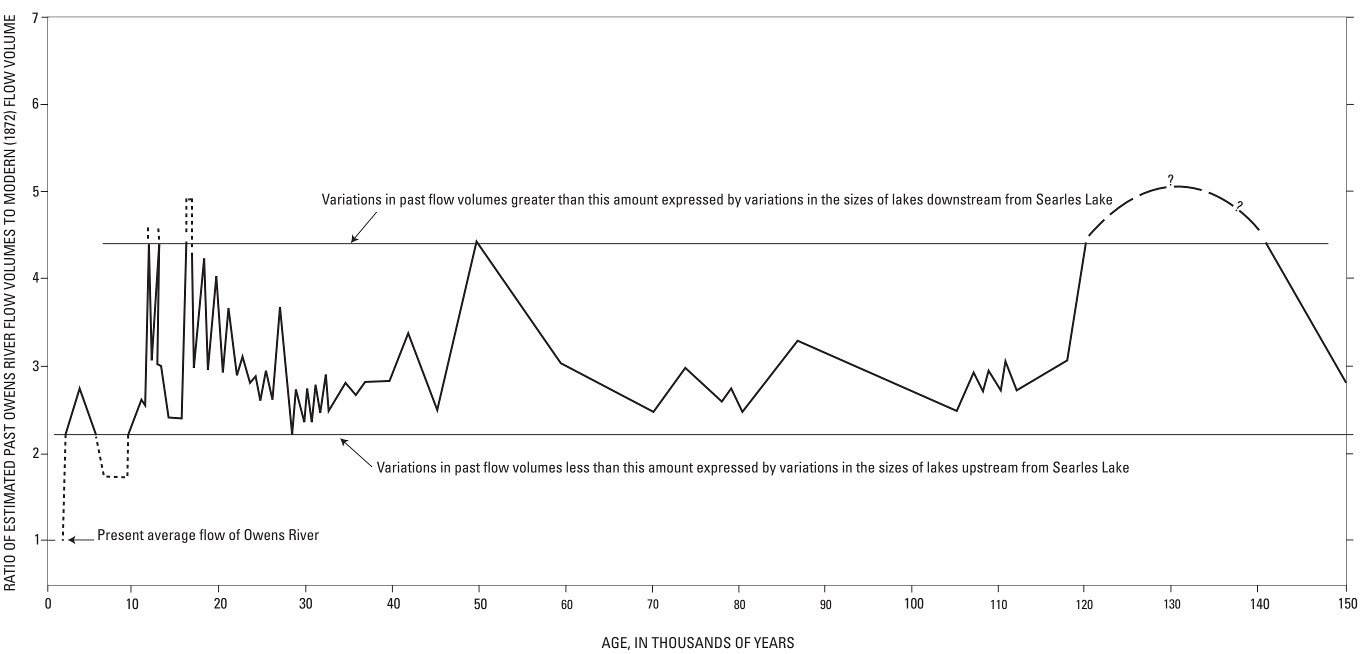


Figure 42. Estimated past flow volumes from the Owens River and tributaries to Owens, China, and Searles Lakes, relative to the modern (1872) flow volume of the Owens River. Calculated past flow volumes are the amounts that would offset evaporation from the surfaces of lakes existing at the time. The evaporation volumes were calculated by assuming that if a lake of any size was in Searles Valley, Owens and China Lake were at their maximum areas, and that the area of Searles lake was proportionate to the levels plotted in figs. 39*C* and 40*C*. The evaporation rates (Owens, 0.89 m/yr; China, 1.02 m/yr, and Searles 1.19 m/yr) assume a 5°C lowering of temperature; the areas of Owens Lake (694 km^2) and China Lake (155 km^2) and the discharge of the modern Owens River (0.41 x 10^9 m^3/yr) are from Smith and Street-Perrott (1983, table 10-2). Area of Searles Lake at different levels derived from Smith (1979, fig. 32); areas of lakes whose levels were beneath the present lake surface are presumed to have been in basins that had the same depth-area characteristics as the present basin.

Paleohydrologic Records for the Period Between 150 and 35 ka

The largest late Pleistocene lake in the Great Basin was Lake Bonneville in northwestern Utah, first studied and named by Gilbert (1890); its modern remnant is the Great Salt Lake. Studies of Lake Bonneville and its chronology up until about 1980 are summarized elsewhere (Smith and Street-Perrott, 1983). Morrison (1991, p. 305-307) concluded that a succession of two or three deep-lake phases existed in Lake Bonneville between 290 and 130 ka. He assigned these ages by correlating their sediments with marine-isotope stages 8 through 6, having concluded that all ^{14}C dates and most U-series dates from Lake Bonneville sediments are too young. Morrison termed the sediments deposited during these lake stages the Alpine Alloformation. Scott and others (1983, p. 280-281, fig. 2), after studying lake sediments at Little Valley in the Bonneville basin, concluded that they represented a brief expansion of Lake Bonneville that occurred after 150 ka and ended about 130 ka. Their age control was based on ^{14}C ages (wood and charcoal), on amino acid ratios in shells, and on the ^{232}Th/^{230}Th dates of Broecker and Kaufman (1965, table 7) and Kaufman and Broecker (1965, table 9). Similarly, Varnes and Van Horn (1984, 1991) reported U-Th dates from the lower part of the Alpine Alloformation ranging from ~108 to ~140 ka.

The evidence indicating a large and overflowing lake in Searles Valley during the period between about 140 ka and 118 ka (fig. 40*C*) is more compatible with the younger ages assigned to the depositional period responsible for the Alpine Alloformation. The Lake Bonneville evidence, however, does not reflect as intense a pluvial period during this time as does the Searles Lake record. Morrison (1991, p. 307) considered the period between 130 and 30 ka, which he assigned to the overlying Promontory Geosol, to be correlative with isotope stages 5 through 3 and to have primarily been one of subaerial deposition. Oviatt and others (1987, fig. 4), however, presented evidence of Lake Bonneville expansions at 65 ka and 40 ka which, although subordinate to the preceding expansion at 140 ka, might be equivalent to the single expansions proposed here for Searles Lake centered at about 50 ka.

Lake Lahontan, a late Pleistocene lake in northwestern Nevada, was first studied and named by Russell (1885). Lake deposits in the several basins making up the Lake Lahontan group have yielded few dates in the range 150 ka to 35 ka. The Eetza Alloformation (Morrison, 1964, 1991) was the first deep-lake phase of the late Pleistocene Lake Lahontan group. Morrison divided its history into three major pulses plus several smaller ones and assigned the formation to the period between about 350 and 130 ka. This age assignment was in large part because of the occurrence of the Wadsworth tephra (~200 to ~150 ka) in the upper part of the alloformation and the Rockland tephra (400 ka) in the upper part of the underlying alloformation (Morrison, 1991, p. 297), and he tentatively correlated it with isotope stages 10 through 6. In the upper part of this alloformation, outcrops of lacustrine sand about halfway between the present low point of the basin and the highest shoreline contained gastropods that gave a ^{230}Th/^{234}U date of 120±20 ka (Broecker and Kaufman, 1965, p. 565, table 7; Kaufman and Broecker, 1965, table 9). Similarly, a ^{230}Th/^{234}U date of approximately 50 ka on high-level tufa suggests that the level of Lake Lahontan at that time was about 90 percent of its maximum depth (Benson and Thompson, 1987a, fig. 5, table 4). If the radiometric dates are about correct, these periods of expansion could be equivalent to the major expansions of Searles Lake postulated for these times (fig. 40*C*).

The wide differences between the ages assigned to the same formations deposited in Lakes Bonneville and Lahontan make it difficult to compare those lakes with the history of Searles Lake between 150 ka and 30 ka. The ages of most lacustrine stages in both Bonneville and Lahontan assigned by Morrison (1991, fig. 5) are 150 ka or older and thus lie outside of the age range being considered here. The younger ages proposed by other workers, based on radiometric and other techniques, correlate approximately with the deep-lake events proposed here for Searles Lake (fig. 40*C*).

Atwater and others (1986, p. 103-104, fig. 6) describe several zones of lacustrine silts beneath the present surface of Tulare Lake, west of the southern Sierra Nevada. Lakes developed in this area during periods of high runoff derived from glaciation in the Sierra Nevada. The lowest of these silt zones, which they term the "West Lake Silt," represents lacustrine expansion that they estimate to have lasted about 30 k.y. within a period bounded by 130 ka and 70 ka. Two or three smaller lacustrine expansions followed during the internal between 70 ka and 26 ka. Considering the differences in the hydrologic settings of Searles Lake and Tulare Lake, which received its water directly from the Sierra Nevada, their records present no conflict as paleoclimatic histories.

Sediments deposited in Pleistocene Lake Chewaucan crop out north of Summer Lake, south-central Oregon. That area is less arid than most of the Pleistocene-lake sites in the Great Basin segments of California, Nevada, and Utah. More than 50 tephra beds provide excellent age control and allow correlations with lacustrine deposits elsewhere. The interbedded sediment lithologies document lacustrine deposition during the entire period between 70 ka and 16 ka, and extrapolation of the indicated sedimentation rates suggests that lacustrine deposition was virtually continuous since some time prior to 335 ka (Davis, 1985, p. 50-51). This suggestion is similar to one based on the Searles Lake record that indicates pluvial to semipluvial conditions existed almost continuously from about 300 ka to 10 ka (Smith, 1986). Davis also notes a possible lake recession, but no evidence of desiccation, that might indicate an interpluvial correlative with interglacial isotope-stage 5e. This recession may also correlate with the succession of intermediate to low stands in the Searles Lake record between about 110 ka and 60 ka (fig. 40*C*).

All four of these lake-basin chronologies, however, show what may be real and important similarities to the reconstructed sequence for Searles Lake during this period. Three of the four basin chronologies find evidence of a highstand that could include the period between 140 and 120 ka, as in Searles Lake, and two find highstands at about 50 ka, as is proposed for Searles. This consistency lends credibility to the accuracy of other details of the several lacustrine histories, despite the variety of hydrologic settings and differing choices of criteria used to compile those histories.

Paleohydrologic Records for the Period Between 35 ka and the Present

A comparison of the paleohydrologic histories indicated by lacustrine deposits in the Great Basin that have been dated in the range 35 ka to the present, based on published and unpublished records from Searles Lake, Lake Lahontan, Lake Bonneville, and Lake Russell (now Mono Lake, in east-central California), is presented by Benson and others (1990). Each lake-level curve differs from the others in certain respects, but detailed comparisons between these areas are inherently difficult, in part because of variations in their basin geometries. Lakes Bonneville and Lahontan were composed of several basins whose lakes coalesced into one water body when nearly full, Lake Russell was in a single basin at the base of the Sierra Nevada, and Searles Lake was two basins downstream from the highest part of the Sierra Nevada, the main source of inflow for the Owens River system.

In Lake Bonneville, the Bonneville Alloformation represents its last major expansion. Morrison (1991, p. 307-308, fig. 13) proposes a history covering this period that shows a gradual rise of the lake starting at ~30 ka and reaching its maximum level at ~16 ka, followed by a rapid decline (caused by a partial breaching of its basin at Red Rock Pass) and then a fall to near desiccation at ~12 ka. This was followed by a short reexpansion, indicated by sediments assigned to the Draper Alloformation, that lasted from 10 to 8 ka. This phase has proven controversial: mapping by Van Horn (1979) shows this unit, but studies by Scott and others (1983), Currey and Oviatt (1985), and Currey (1990), although reconstructing histories for the period 30 to 12 ka similar to that of Morrison (1991), do not recognize the Draper phase. Between 3.7 ka and 1.7 ka, a shallow lake reoccupied the low parts of the basin (Van Horn, 1979).

In Lake Lahontan, northwestern Nevada, the Sehoo Alloformation records the period between 35 ka and 8 ka. Morrison (1991, p. 298-299) divided the Sehoo into three periods that were characterized by deep lakes, separated by relatively low stands. The deep-lake intervals extended from ~35 ka to ~18.5 ka, ~17.5 ka to ~11.5 ka, and ~9 ka to ~8 ka. His ages are largely based on the stratigraphic positions of dated volcanic ash layers. Benson and others (1990, p. 246-249) propose a chronology for the same period that places highstands during periods between ~35 ka and 16 ka, ~15 ka and ~13.5 ka, and a small expansion between ~11.5 ka and ~10 ka; these ages are based primarily on ^{14}C and U-series determinations. The first of these highstands was briefly interrupted by a low stand at ~26 ka, based on a single ^{14}C date.

Neither of the chronologies for Lakes Bonneville and Lahontan closely resembles the Searles Lake chronology for the period between 35 ka and the present. As explained earlier, Searles Lake probably should not have a history that is similar to those lakes because their histories are largely based on work carried out in basins that received runoff directly from the adjoining high mountains. Searles Lake, in contrast, was the third lake in the Owens River system and was surrounded by relatively low mountains.

Additional variations in their reconstructed histories are to be expected in view of possibly real differences in the exact timing of climate change in each drainage area and significant differences in the criteria and methods used to date and reconstruct lake-level curves. In an attempt to minimize the differences between lake histories, Benson and others (1990) offer alternative interpretations for three lakes, including the Searles Lake history as presented by Smith and Street-Perrott (1983, fig. 10-5). His alternative lake-level history for Searles Lake resembles somewhat the history proposed in this paper (fig. 39*C*), but it suggests lower lake levels during the period between 24 ka and 16 ka in unit B time and during all of unit C time, and he questions the existence of the Holocene lake represented by unit D. Those suggestions clearly conflict with the stratigraphic data presented in this paper.

Tulare Lake, west of the southern Sierra Nevada in the San Joaquin Valley, expanded twice since 35 ka, in response to variations in Sierran runoff (Atwater and others, 1986, p. 101-103, fig. 6). The earlier expansion resulted in continuous lacustrine deposition of the Chatom Silt over a period that lasted from about 26 ka to sometime before 13 ka; deposition of the overlying lacustrine Blakeley Canal silt, at about 11 ka, documented a renewed episode of deep-water deposition. The Chatom silt is a reasonable correlative of unit B in Searles Valley, and the Blakely Canal silt appears correlative with unit C. Tulare Lake expansions are interpreted as likely indicators of glaciation pulses in the Sierra Nevada (Atwater and others, 1986, p. 107-109), as are Searles Lake expansions.

South of the Great Basin, in central New Mexico, Lake Estancia had a late Pleistocene history that was mostly similar to those of lakes in the Great Basin (Bachhuber, 1989; the ages cited below were derived by my interpolating and extrapolating between the three ^{14}C dates considered by him to be reliable: 24,300, 20,040, and 12,460 yr B.P.). In a reconstructed record starting before 35 ka, an “initial freshwater phase” began about 24.5 ka. Although the maximum inferred water depth was reached about 19.7 ka, the mostly freshwater lake persisted until about 16.0 ka. Playa deposits represent the interval between 16.0 ka and 13.5 ka. A second period characterized by freshwater deposits followed, and the lake reached its maximum freshness around 12.5 ka. Soils started forming on the older deposits around 10.7 ka. This sequence of stages and their ages are similar to those from both the Tulare Lake and Searles Lake records.

Another type of paleohydrologic record, studied in three areas northwest of Las Vegas, Nevada, consists of alternating alluvial and paludal (marsh) environments, with each change in depositional environment separated by a period of soil development. The initial studies of Haynes (1967) in the Tule Springs area and subsequent studies by Quade (1986, fig. 2) in the Corn Creek Springs area show that the marshes in their areas appear to have had the following histories: (1) They were dry or possibly dry from sometime before 35 ka or 32 ka. (2) Then, after development of a strong noncalcic soil, wet conditions prevailed until 16 ka. (3) After development of a moderate to strong calcic soil, wet to moist conditions, indicated by spring and marsh deposits, mollusks, and plants (separated by a short period represented locally by a weak soil), prevailed until about 8 ka. (4) Finally, dry conditions existed until the present. A third study in the nearby Cactus Spring area (Quade and Pratt, 1989, fig. 4) involved similar deposits but found no evidence of a depositional hiatus at the 16-ka horizon. The noncalcic soils developed in both of these areas at about 30 ka are possibly correlative with the (normally) noncalcic soil that formed at about 24 ka on unit AB in Searles Valley, marking the end of an intermittently dry period and the start of a wet one (unit B). The 14-ka calcic soil in the Corn Springs area may be equivalent to the soil on unit BC in Searles Valley that separates a long period of wet conditions, which ended at about 15.5 ka (unit B), from a short period characterized by fluctuating wet conditions that started at about 13.5 ka (unit C).

The two or three reexpansions of Searles Lake during the short interval between 13.5 ka and 10.5 ka, documented by deposits of unit C, have small counterparts in the Lake Bonneville record, which indicates a lake-level rise of about 25 m between 11 ka and 10 ka, and in the Lake Lahontan record, which includes a rise of about 10 m above the highest historic level of Pyramid Lake at about 11 ka, but no support is found in the record from Lake Russell (Benson and others, 1990, p. 249, 258, figs. 4, 7, 14). The Searles Lake history, however, may reflect its sensitivity to short climatic variations because of the lake's small size and position in the chain of lakes. At its maximum size, Searles Lake, including China Lake with which it coalesced, had an area that was 5 percent and 2 percent, respectively, of the areas of Lakes Lahontan and Bonneville. Therefore, a few centuries of very intense inflow into Searles Valley could have filled the basin, whereas the same volumetric increase in inflow to the larger basins would not have caused a major increase in lake level. Furthermore, the low-level, but perennial, character of the lake responsible for unit BC suggests that Owens and China Lakes contained water during this period and intermittently contributed overflow to Searles Valley. Under this condition, almost 100 percent of any increase in runoff from the Owens Lake watershed, caused by an increase in regional precipitation, would have immediately reached and started raising the level of Searles Lake.

Several other records from areas nearer the latitude of Searles Lake, however, indicate a wet period at about 12 ka. The paludal records from northwestern Las Vegas Valley (Quade, 1986, fig. 2) show two separate periods that represent moist conditions during the interval between about 13 ka and 8 ka, and these may be more complete records of the same climatic events as recorded in truncated form by the sediments of unit C in Searles Valley.

In Death Valley, dates on the organic ^{14}C in three core segments composed of black to green lacustrine silt and clay fall near 21.5 ka, 13 ka, and 12 ka (Hooke, 1972, fig. 3, table 3). These came from the 10-km-wide segment of the valley floor that includes its lowest elevations, implying the existence of perennial lakes of that width until sometime after 12 ka. Thirty-seven ^{14}C dates and numerous artifacts from Silver Lake, 90 km southeast of the lowest part of Death Valley and now the occasional sump of the Mojave River, date pluvial events in that area. An earlier study showed that the lake receded from its highest stand (10 m) about 14.5 ka, but readvances occurred during the periods 13.75 ka to 12 ka, 11 ka to 9 ka, and 8.5 ka to 7.5 ka (Ore and Warren, 1971, fig. 7). The expansion starting at 11 ka eroded the lake's outlet 2 m deeper, suggesting that this episode was characterized by a relatively larger-than-normal volume of overflow. A later study, based on outcrops, trenches, and cores, revealed a more complex history, but one that indicated a major drying event at 15.5 ka, a refilling event at 13.7 ka, a termination of that nearly continuous high stand at 11.5 ka, and the end of an intermittent-level lake at 8.7 ka (Wells and others, 1989, figs. 24 and 25).

Nelson Lake, a small (2 km^2), hard-surface playa lying 55 km southeast of Searles Lake, is rimmed on its southeast side by well preserved beach and bar deposits indicating a 2-m-deep lake; cultural materials along the crest of the bar, whose ages are considered to be 11 to 10 ka (Bachhuber, 1984, p. 595; Warren and Schneider, 1989, p. 18, fig. 1), show that the bar is at least that old. Inasmuch as Nelson Lake, at an elevation of 930 m, receives drainage from an area of only about 225 km^2 that includes no mountains more than 600 m above the lake surface, this water body seems to document at least one intense wet episode in very late Quaternary time. McLean Lake, 6 km north of Nelson Lake, appears on aerial photographs to have a similarly developed bar along its southeast edge.

The segment of the Searles Lake paleohydrologic record from 10 ka to 6 ka (fig. 39*C*) documents dry conditions, as does some part of almost every other lacustrine record from the Great Basin (Smith and Street-Perrott, 1983, fig. 10-6). The record of a 60-m-deep lake in Searles Valley, whose age is constrained by one ^{14}C age on wood (3.5 ka), leaves the ages of its rise and fall unconstrained. Its rise could have been contemporaneous with an 85-m rise in the level of Walker Lake, a remnant of Lake Lahontan, that postdates 4.7 ka (Benson and Thompson, 1987a, fig. 5), or with the 15-m to 20-m fluctuations in Great Salt Lake, the remnant of Lake Bonneville, at about 3.5 ka and 2.3 ka (Spencer and others, 1984, p. 332). Lake Russell (now Mono Lake) also indicates a rise of about 30 m, starting possibly as early as 7.0 ka and reaching maximum level by 3.5 ka (Stine, 1990, p. 365; Benson and others, 1990, fig. 14). A shallow water body in Silver (dry) Lake, 125 km southeast of Searles Lake, developed over a short period that centered near 3.6 ka (Enzel and others, 1989, p. 44, fig. 1b).

Comparison with History of High-Latitude Glaciation

The basal age of the Bottom Mud at Searles Lake (described earlier) is apparently correlative with the onset of termination 2, the end of the next-to-last major glacial period (Martinson and others,1987, fig. 18, table 2; Johnson, 1991). However, if the Searles Lake fluctuations described herein at 150 ka and the high-latitude glacial fluctuations termed termination 2 at 127 ka as described by Martinson and others (1987) are correlated, they lie 23 k.y. apart. If we use 130 ka as the age of the base of the Bottom Mud, this contact would almost coincide temporally with the termination of the Oxygen Isotope Stage (OIS) 6 glaciation according to marine records, but strong evidence assembled by others indicates an earlier date for termination 2. Johnson (1991) suggests that sea-level rise and concurrent ice-sheet melting actually started at about 140 ka, 13 k.y. before 127 ka, and Stein and others (1993) conclude that sea-level rise began nearer to 134 ka and ended near 118 ka. In addition, the well documented evidence for pronounced climatic warming at about 140 ka is recorded in vein calcite at Devils Hole, Nevada, an area about 100 km northeast of Searles Lake (Winograd and others, 1992, p. 257). Thus, the Searles Lake record and the marine and nonmarine records published in the 1990s indicate closer ages for what seem like reasonably correlated events. A problem, however, is that the rise in Searles Lake at that time coincides temporally with both the deep-sea and Devils Hole records of a warming trend, whereas much of the evidence, and most of the initial modeling of global climates, relates pluvial periods to glacial periods; this is discussed in more detail below.

The Searles Lake fluctuations since 35 ka (fig. 39*C*), for which age control is better than for older deposits, again have an uneven record of correspondence with high-latitude glacial events. The contact between the Bottom Mud and Lower Salt at 32 ka does not correspond with any significant change in the marine isotopic record of high-latitude glaciation (Bischoff and others, 1985, fig. 2; Martinson and others, 1987, fig. 18, table 2). The brief lacustrine desiccation at 28 ka in Searles Lake corresponds only with minor fluctuations in the marine isotopic record, but that event and several adjoining periods of less extreme lake fluctuations have been tentatively related to stadial-interstadial fluctuations recorded by an ice core from Greenland (Phillips and others, 1994). Also, the period represented by the Lower Salt subunits S6 and S7 (28 ka to 24 ka), considered on the basis of salt mineralogy to have been deposited at times ambient temperatures were about 5°C cooler than those characterizing earlier salt deposition (Smith, 1979, p. 89-90), corresponds approximately with the ages of deposits representing the cold Farmdalian interglacial period in the ice-sheet history of the northeastern United States (Follmer, 1983, p. 141, fig. 7-2; Baker and others, 1989, p. 1375).

Searles Lake overflow at 16 ka could correspond with either the 18 ka glacial maximum or the subsequent trend toward deglaciation. The major—but very brief—lake fluctuations between 13.5 ka and 10.5 ka have no counterpart in the ice-sheet history as derived from the marine record. They do, however, approximately correspond in time with oscillations of the ice-sheet margin in the northern Great Lakes region of the United States (Mickelson and others, 1983, p. 25-26) and with water-temperature changes in the North Atlantic Ocean that produced very rapid temperature changes, termed the Allerod-Dryas oscillations, in the adjoining continental areas (Ruddiman and McIntyre, 1981, p. 178-182, 185-191; Broecker and others, 1985, p. 23-25). If the Allerod-Dryas climatic oscillations, which have been considered events that occurred only in the North Atlantic's climatic sphere of influence (Broecker and others, 1985, p. 24; Broecker and Denton, 1989, p. 2481), were in fact expressed also in this part of the western United States, it may reflect a history of changes in the western United States (Haynes, 1991, p. 447, fig. 6) and the Northeast Pacific Ocean (Mathewes and others, 1993, p. 104) that resembled those reconstructed for the North Atlantic by Ruddiman and McIntyre (1981). DeDecker and others (1991) report evidence from an area just north of Australia that indicates a dry event that had the same age and duration as the Dryas cold event, implying that this short climatic event was expressed in some manner worldwide.

Overall, changes in Searles Lake levels show an inconsistent relation to high-latitude glacial fluctuations, and establishing the ages and directions of middle-latitude climatic changes on the basis of deep-sea isotopic chronologies appears to be a risky practice. The best example of this is provided by a review of Searles Lake's fluctuations that accompanied the last two apparently rapid terminations of high-latitude glaciations indicated by isotopic data from deep-sea cores. As noted earlier, ice-sheet melting during the period that deep-sea records indicate was between 135 ka and 125 ka (OIS 5/6 boundary) approximately coincided with the sustained expansion of Searles Lake and probable overflowing into Panamint Valley (regardless which age is used for the base of the Bottom Mud), as well as with warming in the Devils Hole record near Death Valley (Winograd and others, 1992, fig. 4). In contrast, the rapid destruction of the next generation of high-latitude ice sheets, between 14 ka and 8 ka (OIS 1/2 boundary), coincided approximately with the near desiccation of Searles Lake between about 15 ka and 13.5 ka, then the brief expansions of the lake between about 13.5 ka and 10.5 ka, and finally again the desiccation of Searles Lake at about 10.5 ka. All of this occurred during the global deglaciation period. Earlier major changes in ice-sheet sizes, as documented by the boundaries between marine OIS 6, 7, 8, and 9, influenced climates in the Searles Lake drainage area so little that they produced no stratigraphic evidence of significant changes in lake size (Smith, 1984, p. 13; Bischoff and others, 1985).

Furthermore, the durations of the most extreme changes in regional precipitation and runoff for this area may have been affected importantly by the Earth's orbital perturbations that have a cycle length of about 413 k.y., a cycle that is well recorded by changes in low-latitude sea-surface temperatures and tropical sea-floor sedimentary carbonate percentages but appears to be unrecorded in ice-sheet chronologies (Smith, 1984, p. 13-14). Shorter astronomical cycles, which have durations of about 100 k.y., 40 k.y., and 20 k.y., appear to have been more important in determining the timing of high-latitude glacial events (Hays and others, 1976). The 100-k.y. cycles are recorded in the Owens Lake record (Smith and others, 1997), but many of them were not of sufficient magnitude to be transmitted downstream to Searles Lake with an intensity that registered in its sedimentary record. The shorter cycles appear responsible for some cyclic changes in the Searles Lake record when the prevailing hydrologic regime was at intermediate levels (fig. 41), but the longer period orbital perturbations seem likely to have been responsible for the major changes in regional hydrology and in the numbers and sizes of lakes in the Owens River chain.

References

Atwater, B.F., Adam, D.P., Bradbury, J.P., Forester, R.M., Mark, R.K., Lettis, W.R., Fisher, G.R., Gobalet, K.W., and Robinson, S.W., 1986, A fan dam for Tulare Lake, California, and implications for the Wisconsin glacial history of the Sierra Nevada: Geological Society of America Bulletin, v. 97, p. 97-109.

Bachhuber, F.W., 1984, Geological aspects of a transect from Archaeological Site 4-SBr-4966 (KD-25) to Nelson Lake and a discussion of the Ridge Quarry Site (4-SBr-4977), Fort Irwin National Training Center, California, *in* An archaeological survey of the 1982 Gallant Eagle Exercise Area, Fort Irwin, San Bernardino County, California: Fort Irwin Archaeological Project Research Report 7, p. 594-602.

Bachhuber, W.F., 1989, The occurrence and paleolimnologic significance of Cutthroat trout (*Onchorhnous clarki*) in pluvial lakes of the Estancia Valley, central New Mexico: Geological Society of America Bulletin, v. 101, p. 1543-1551.

Baker, R.G., Sullivan, A.E., Hallberg, G.R., and Horton, D.G., 1989, Vegetational changes in western Illinois during the onset of late Wisconsinan glaciation: Ecology, v. 70, p. 1363-1376.

Benson, L.V., 1978, Fluctuation in the level of the pluvial Lake Lahontan during the last 40,000 years: Quaternary Research, v. 9, p. 300-318.

Benson, L.V., 1981, Paleoclimatic significance of lake level fluctuations in the Lahontan Basin: Quaternary Research, v. 16, p. 390-403.

Benson, L.V., 1986, The sensitivity of evaporation rate to climate change—results of an energy-balance approach: U.S. Geological Survey Water-Resources Investigations Report 86-4148, 40 p.

Benson, L.V., and Paillet, F.L., 1989, The use of total lake-surface area as an indicator of climatic change; examples from the Lahontan basin: Quaternary Research, v. 32, p. 262-275.

Benson, L.V., and Thompson, R.S., 1987a, Lake-level variation in the Lahontan Basin for the past 50,000 years: Quaternary Research, v. 28, p. 69-85.

Benson, L.V., and Thompson, R.S., 1987b, The physical record of lakes in the Great Basin, *in* Ruddiman, W.F., and Wright, H.E., Jr., eds., North America and adjacent oceans during the last deglaciation: Geological Society of America, The Geology of North America, v. K-3, p. 241-260.

Benson, L.V., Currey, D.R., Dorn, R.I., Lajoie, K.R., Oviatt, C.G., Robinson, S.W., Smith, G.I., and Stine, S., 1990, Chronology of expansion and contraction of four Great Basin lake systems during the past 35,000 years: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 78, p. 241-286.

Bischoff, J.L., Fitts, J.P., and Fitzpatrick, J.A., 1997, Responses of sediment chemistry to climate change in Owens Lake sediments; an 800-ky record of saline/fresh cycles in Core OL-92, *in* Smith, G.I., and Bischoff, J.L., eds., An 800,000-year paleoclimatic record from core OL-92, Owens Lake, southeast California: Geological Society of America Special Paper 317, p. 37-47.

Bischoff, J.L., Rosenbauer, R.J., and Smith, G.I., 1985, Uranium-series dating of sediments from Searles Lake; differences between continental and marine climate records: Science, v. 227, p. 1222-1224.

Broecker, W.S., and Denton, G.H., 1989, The role of ocean-atmosphere reorganizations in glacial cycles: Geochimica et Cosmochimica Acta, v. 53, no. 10, p. 2465-2501.

Broecker, W.S., and Kaufman, A., 1965, Radiocarbon chronology of Lake Lahontan and Lake Bonneville II, Great Basin: Geological Society of America Bulletin, v. 76, p. 537-566.

Broecker, W.S., and Walton, A., 1959, Geochemistry of C^{14} in freshwater systems: Geochimica et Cosmochimica Acta, v. 16, p. 15-38.

Broecker, W.S., Peteet, D.M., and Rind, David, 1985, Does the ocean-atmosphere system have more than one stable mode of operation?: Nature, v. 315, p. 21-26.

Butler, P.R. and Mount, J.F., 1986, Corroded cobbles in southern Death Valley; their relationship to honeycomb weathering and lake shorelines: Earth Surface Processes and Landforms, v. 11, p. 377-387.

Carter, B.A., 1987, Quaternary fault-line features of the central Garlock fault, Kern County, California: Geological Society of America Centennial Field Guide, p. 133-135.

Cerling, T.E., 1990, Dating geomorphic surfaces using cosmogenic ^3He: Quaternary Research, v. 33, p. 148-156.

Chadwick, O.A., and Davis, J.O., 1990, Soil-forming intervals caused by eolian sediment pulses in the Lahontan Basin, northwestern Nevada: Geology, v. 18, p. 243-246.

Clark, M.M., 1973, Map showing recently active breaks along the Garlock and associated faults, California: U.S. Geological Survey Miscellaneous Geologic Investigations, Map I-741.

Clifton, H.E., 1973, Pebble segregation and bed lenticularity in wave-worked versus alluvial gravel: Sedimentology, v. 20, p. 173-187.

Cloud, P.E., Jr., and Lajoie, K.R., 1980, Calcite-impregnated defluidization structures in littoral sands of Mono Lake, California: Science, v. 210, p. 1009-1012.

Currey, D.R., 1990, Quaternary paleolakes in the evolution of semidesert basins, with special emphasis on Lake Bonneville and the Great Basin, U.S.A.: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 76, p. 189-214.

Currey, D.R., and Oviatt, C.G., 1985, Durations, average rates, and probable causes of Lake Bonneville expansions, stillstands, and contractions during the last deep-lake cycle, 32,000 to 10,000 years ago, *in* Kay, P.A., and Diaz, H.F., eds., Problems of and prospects for predicting Great Salt Lake levels: Salt Lake City, Center for Public Affairs Administration, University of Utah, p. 9-24.

Davis, E.L., and Panlaqui, Carol, 1978, Present and past environments of the valley, chap.2 *of* Davis, E.L., ed., The ancient Californians, Rancholabrean hunters of the Mojave lakes country: Natural History Museum of Los Angeles County, Science Series 29, p. 14-21.

Davis, Jonathan, 1985, Correlation of late Quaternary tephra layers in a long pluvial sequence near Summer Lake, Oregon: Quaternary Research, v. 23, no. 1, p. 38-53.

DeDecker, Patrick, Correje, Thierry, and Head, John, 1991, Late Pleistocene record of cyclic eolian activity from tropical Australia suggesting the Younger Dryas is not an unusual event: Geology, v. 19, p. 602-605.

Duffield, W.A., and Bacon, C.R., 1981, Geologic map of the Coso volcanic field and adjacent areas, Inyo County, California: U.S. Geological Survey Miscellaneous Investigations Series, Map I-1200, scale 1:50,000.

Enzel, Y., Cayan, D.R., Anderson, R.Y., and Wells, S.G., 1989, Atmospheric circulation during Holocene lake stands in the Mojave Desert; evidence of regional climate change: Nature, v. 341, p. 44-47.

Fairbanks, H.W., 1896, Notes on the geology of eastern California: American Geologist, v. 17, p. 63-74.

Folk, R.L., and Ward, W.C., 1957, Brazos River bar; a study in the significance of grain size parameters: Journal of Sedimentary Petrology, v. 27, p. 3-26.

Follmer, L.R., 1983, Sangamon and Wisconsinan pedogenesis in the midwestern United States, chap. 7 *of* Wright, H.E., Jr., ed., Late-Quaternary environments of the United States: Minneapolis, University of Minnesota Press, p. 138-144.

Fortsch, D.E., 1978, The Lake China Rancholabrean faunule, chap. 8 *of* Davis, E.L., ed., The ancient Californians, Rancholabrean hunters of the Mojave lakes country: Natural History Museum of Los Angeles County, Science Series 29, p. 173-176.

Friedman, Irving, Smith, G.I., and Hardcastle, K.G., 1976, Studies of Quaternary saline lakes, II. Isotopic and compositional changes during desiccation of the brines in Owens Lake, California, 1969-1971: Geochimica et Cosmochimica Acta, v. 40, p. 501-511.

Gale, H.S., 1914, Salines in the Owens, Searles, and Panamint basins, southeastern California: U.S. Geological Survey Bulletin 580-L, p. 251-321.

Garcia, J.F., Bischoff, J.L., Smith, G.I., and Trimble, D., 1993, Uranium-series and radiocarbon dates on tufas from Searles Lakes, California: U.S. Geological Survey Open-File Report 93-311, 8 p.

Gilbert, G.K., 1890, Lake Bonneville: U.S. Geological Survey Monograph 1, 438 p.

Goddard, E.N., 1951, Rock-color chart: Boulder, Colo., Geological Society of America.

Haines, D.V., 1957, Core logs from Searles Lake, San Bernardino County, California: U.S. Geological Survey Open-File Report 1957-40, 1010 p.

Haines, D.V., 1959, Core logs from Searles Lake, San Bernardino County, California: U.S. Geological Survey Bulletin 1045-E, p. 138-317.

Halley, E., 1715, On the cause of the saltness of the ocean, and of the several lakes that emit no rivers: Philosophical Transactions of the Royal Society of London, v. 6, p. 169.

Handbook of Chemistry and Physics, 1966: Cleveland, Ohio, The Chemical Rubber Co., 47th Edition.

Hanna, G.D., 1963, Some Pleistocene and Pliocene freshwater mollusca from California and Oregon: Occasional Papers of the California Academy of Sciences, no. 43, 20 p.

Hay, R.L., and Guldman, S.G., 1987, Diagenetic alteration of silicic ash in Searles Lake, California: Clays and Clay Minerals, v. 35, no. 6, p. 449-457.

Hay, R.L., Guldman, S.G., Matthews, J.C., Lander, R.H., Duffin, M.E., and Kyser, T.K., 1991, Clay mineral diagenesis in core KM-3 of Searles Lake, California: Clay and Clay Minerals, v. 39, p. 84-96.

Haynes, C.V., 1967, Quaternary geology of the Tule Springs arm, Clark County, Nevada, *in* Worthingon, H.M., and Ellis, D., eds., Pleistocene studies in southern Nevada: Nevada State Museum Anthropological Papers, No. 13, p. 15-104.

Haynes, C.V., Jr., 1991, Geoarcheological and paleohydrological evidence for a Clovis-age drought in North America and its bearing on extinction: Quaternary Research, v. 35, p. 438-450.

Hays, J.D., Imbrie, J., and Shackleton, N.J., 1976, Variations in the earth's orbit— pacemaker of the ice ages: Science, v. 194, 1121-1132.

Hooke, R. LeB., 1972, Geomorphic evidence for late-Wisconsin and Holocene tectonic deformation, Death Valley, California: Geological Society of America Bulletin, v. 83, p. 2073-2098.

Huber, N.K., 1981, Amount and timing of Late Cenozoic uplift and tilt of the central Sierra Nevada, California—evidence from the upper San Joaquin River Basin: U.S. Geological Survey Professional Paper 1197, 28 p.

Hutchinson, G.E., 1937, A contribution to the limnology of arid regions: Transactions of the Connecticut Academy of Arts and Sciences, v. 33, p. 47-132.

Hutchinson, G.E., 1957, A treatise on limnology, v. 1, Geography, physics, and chemistry: New York, John Wiley and Sons, Inc., 1015 p.

Inman, D.L., 1952, Measures for describing the size distribution of sediments: Journal of Sedimentary Petrology, v. 22, p. 125-145.

Izett, G.A., and Wilcox, R.E., 1982, Map showing localities and inferred distributions of the Huckleberry Ridge, Mesa Falls, and Lava Creek ash beds (Pearlette Family Ash Beds) of Pliocene and Pleistocene Age in the Western United States and Southern Canada: U.S. Geological Survey Miscellaneous Investigation Series, Map I-1325, scale 1:4,000,000.

Izett, G.A., Pierce, K.L., Naeser, N.D., and Jaworowski, C, 1992, Isotopic dating of Lava Creek B tephra in terrace deposits along the Wind River, Wyoming—implications for post 0.6 Ma uplift of the Yellowstone hotspot: Geological Society of America Abstracts with Programs, v. 24, no. 7, p. 102A.

Jannik, N.O., 1989, Lake history in the paleo-Owens River system, California, for the past 2.0 m.y. based on ^{36}Cl dating of the evaporites from Searles Lake: Socorro, New Mexico, New Mexico Institute of Mining and Technology, Ph.D. dissertation, 134 p.

Johnson, R.G., 1991, Major Northern Hemisphere deglaciation caused by a moisture deficit 140 ka: Geology, v. 19, p. 686-689.

Kaufman, Aaron, and Broecker, W.S., 1965, Comparison of Th^{230} and C^{14} ages for carbonate materials from Lakes Lahontan and Bonneville: Journal of Geophysical Research, v. 70, no. 16, p. 4039-4054.

Kempe, S., Kazmierczak, J., Landmann, G., Konuk, T., Reimer, A., and Lipp, A., 1991, Largest known microbialites discovered in Lake Van, Turkey: Nature, v. 349, p. 605-608.

Kerr-McGee Corporation, 1986, Annual Report: Oklahoma City, 54 p.

Krumbein, W.C., 1934, Size frequency distribution of sediments: Journal of Sedimentary Petrology, v. 4, p. 65-77.

Langbein, W.B., 1961, Salinity and hydrology of closed lakes: U.S. Geological Survey Professional Paper 412, 20 p.

Lanphere, M.A., Champion, D.E., Christiansen, R.L., Izett, G.A., and Obradovich, J.D., 2002, Revised ages for tuffs of the Yellowstone Plateau volcanic field; assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event: Geological Society of America Bulletin, v. 114, no. 5, p. 559-568.

Mabey, D.R., 1956, Geophysical studies in southern California basins: Geophysics, v. 21, no. 3, p. 839-853.

Machette, M.N., 1985, Calcic soils of the southwestern United States, *in* Weide, D.L., ed., Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 1-21.

Mankiewicz, P.J., 1975, An organic geochemical investigation of a glacial sequence at Searles Lake, California: Los Angeles, University of California, Masters thesis, 122 p.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, John, Moore, T.C., Jr., and Shackleton, N.J., 1987, Age dating and the orbital theory of the Ice Ages; development of a high-resolution 0 to 300,000-year chronostratigraphy: Quaternary Research, v. 27, no. 1, p. 1-29.

Mason, C.C., and Folk, R.L., 1958, Differentiation of beach, dune, and aeolian flat environments by size analysis, Mustang Island, Texas: Journal of Sedimentary Petrology, v. 28, no. 2, p. 211-226.

Mason, D.T., 1967, Limnology of Mono Lake, California: Berkeley and Los Angeles, University of California Press, University of California Publications in Zoology, v. 83, 110 p.

Mathewes, R.W., Heusser, L.E., and Patterson, R.T., 1993, Evidence for a Younger Dryas-like cooling event on the British Columbia coast: Geology, v. 21, p. 101-104.

Mehringer, P.J., and Sheppard, J.C., 1978. Holocene history of Little Lake, Mojave Desert, California, chap. 6 *of* Davis, M.L., ed., The ancient Californians, Rancholabrean hunters of the Mojave lakes country: Natural History Museum of Los Angeles County, Science Series 29, p. 153-166.

Mickelson, D.M., Clayton, L., Fullerton, D. S., and Borns, H.W., Jr., 1983, The late Wisconsin glacial record of the Laurentide Ice Sheet in the United States, chap. 1 *of* Wright, H E., Jr., ed., Late-Quaternary environments of the United States: Minneapolis, University of Minnesota Press, p. 1-37.

Moore, S.C., 1976, Geology and thrust fault tectonics of the Argus and Slate Ranges, California: Seattle, Washington, University of Washington, Ph.D. dissertation, 127 p.

Morrison, R.B., 1964, Lake Lahontan; geology of southern Carson Desert, Nevada: U.S. Geological Survey Professional Paper 401, 156 p.

Morrison, R.B., 1991, Quaternary stratigraphic, hydrologic, and climatic history of the Great Basin, with emphasis on Lakes Lahontan, Bonneville, and Tecopa, *in* Morrison, R.B., ed., Quaternary nonglacial geology; conterminous U.S: Boulder, Colorado, The Geological Society of America, The Geology of North America, v. K-2, p.283-320.

National Oceanic and Atmospheric Administration, 1982, Monthly normals of temperature, precipitation, and heating and cooling degree days, 1951-80, California: Asheville, N.C., National Climatic Center, Climatography of the United States No. 81.

Noble, L.F., 1931, Nitrate deposits in southeastern California with notes on deposits in southeastern Arizona and southwestern New Mexico: U.S. Geological Survey Bulletin 820, 108 p.

Ore, H.T., and Warren, C.N., 1971, Late Pleistocene-early Holocene geomorphic history of Lake Mojave, California: Geological Society of America Bulletin, v. 82, p. 2553-2562.

Oviatt, C.G., McCoy, W.D., and Reider, R.G., 1987, Evidence for a shallow early or middle Wisconsin-age lake in the Bonneville basin, Utah: Quaternary Research, v. 27, p. 248-262.

Peng, T.H., Goddard, J.G., and Broecker, W.S., 1978, A direct comparison of ^{14}C and ^{230}Th ages at Searles Lake, California: Quaternary Research, v. 9, p. 319-329.

Phillips, F.M., Campbell, A.R., Smith, G.I., and Bischoff, J.L., 1994, Interstadial climatic cycles; a link between western North America and Greenland?: Geology, v. 22, p. 1115-1118.

Ponti, D.J., 1985, The Quaternary alluvial sequence of the Antelope Valley, California, *in* Weide, D.L., ed., Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 79-96.

Quade, J., 1986, Late Quaternary environmental changes in the upper Las Vegas Valley, Nevada: Quaternary Research, v. 26, p. 340-357.

Quade, Jay, and Pratt, W.L., 1989, Late Wisconsin groundwater discharge environments of the southwestern Indian Springs Valley, southern Nevada: Quaternary Research, v. 31, p. 351-370.

Rigby, J.K., and Hamblin, W.K., eds., 1972, Recognition of ancient sedimentary environments: Society of Economic Paleontologists and Mineralogists, Special Publication 16, 340 p.

Roosma, Aino, 1958, A climatic record from Searles Lake, California: Science, v. 128, no. 3326, p. 123, 127.

Ruddiman, W.F., and McIntyre, Andrew, 1981, The north Atlantic during the last deglaciation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 35, p. 145-214.

Russell, I.C., 1885, Geological history of Lake Lahontan, a Quaternary lake of northwestern Nevada: U.S. Geological Survey Monograph 11, 287 p.

Russell, I.C., 1889, Quaternary history of Mono Valley, California: Eighth Annual Report of the United States Geological Survey, 1886-7, p. 261-394.

Ruttner, F., 1953, Fundamentals of limnology, *translated by* Frey, D.G., and Fry, F.E.J.: Toronto, University of Toronto Press, 242 p.

Scholl, D.W., 1960, Pleistocene algal pinnacles at Searles Lake, California: Journal of Sedimentary Petrology, v. 30, p. 414-431.

Scholl, D.W., and Taft, W.H., 1964, Algae, contributors to the formation of calcareous tufa, Mono Lake, California: Journal of Sedimentary Petrology, v. 34, p. 309-319.

Scholl, D.W., von Huene, R., St. Amand, P., and Ridlon, J.B., 1967, Age and origin of topography beneath Mono Lake, a remnant Pleistocene lake, California: Geological Society of America Bulletin, v. 78, p. 583-600.

Schumm, S.A., 1965, Quaternary paleohydrology, *in* Wright, H.E., and Frey, D.G., eds., The Quaternary of the United States: Princeton, New Jersey, Princeton University Press, p. 783-794.

Schweig, E.S., III, 1984, Neogene tectonics and paleogeography of the southwestern Great Basin, Inyo County, California: Palo Alto, California, Stanford University, Ph.D. dissertation, 207p.

Scott, W.E., McCoy, W.D., Shroba, R.R., and Rubin, M., 1983, Reinterpretation of the exposed record of the last two cycles of Lake Bonneville, western United States: Quaternary Research, v. 20, no. 3, p. 261-285.

Sheppard, R.A., and Gude, A.J., 3d, 1968, Distribution and genesis of authigenic silicate minerals in tuffs of Pleistocene Lake Tecopa, Inyo County, California: U.S. Geological Survey Professional Paper 597, 38 p.

Skinner, B.J., 1966, Thermal expansion, *in* Clark, S.P., Jr., ed., Handbook of Physical Constants: Geological Society of America, p. 75-96.

Smith, G.I., 1962, Large lateral displacement on the Garlock fault, California, as measured from offset dike swarm: American Association of Petroleum Geologists Bulletin, v. 46, p. 85-105.

Smith, G.I., 1964, Geology and volcanic petrology of the Lava Mountains, San Bernardino County, California: U.S. Geological Survey Professional Paper 457, 97 p.

Smith, G.I., 1966a, A comparison of two terrestrial grabens with the lunar rilles Rima Ariadaeus and Rimae Hypatia I and II: U.S. Geological Survey, Astrogeologic Studies Annual Progress Report, 20 p.

Smith, G.I., 1966b, Geology of Searles Lake—a guide to prospecting for buried continental salines: Northern Ohio Geological Society, Second Symposium on Salt, Cleveland, Ohio, v. 1, p. 167-180.

Smith, G.I., 1976, Origin of lithium and other components in the Searles Lake evaporites, *in* Vine, J.D., ed., Lithium resources and requirements by the year 2000: U.S. Geological Survey Professional Paper 1005, p. 92-103.

Smith, G.I., 1979, Subsurface stratigraphy and geochemistry of late Quaternary evaporites, Searles Lake, California: U.S. Geological Survey Professional Paper 1043, 130 p.

Smith, G.I., 1984, Paleohydrologic regimes in the southwest Great Basin, 0-3.2 m.y. ago, compared with other long records of “global” climate: Quaternary Research, v. 22, p. 1-17.

Smith, G.I., 1986, A case for three (and only three) pluvial periods in southeastern California during the past 3 m.y.: Los Angeles, Geological Society of America, Cordilleran Section, Program and abstracts for 82nd Annual Meeting.

Smith, G.I., 1987, Searles Valley, California; outcrop evidence of a Pleistocene lake and its fluctuations, limnology, and climatic significance, *in* Hill, M.L., ed., Cordilleran Section of the Geological Society of America: Boulder, Colorado, Geological Society of America, Centennial Field Guide, v. 1, p. 137-142.

Smith, G.I., 1990, Searles Lake, California; a multi-billion dollar “salt” deposit: Reno, Nevada, Geological Society of Nevada and U.S. Geological Survey, Symposium of the Geology and Ore Deposits of the Great Basin, Program with abstracts, p. 124.

Smith, G.I., 1991a, Anomalous folds associated with the east-central part of the Garlock fault, southeast California: Geological Society of America Bulletin, v. 103, p. 615-624.

Smith, G.I., 1991b, Continental paleoclimatic records and their significance, *in* Smiley, T.L., and others, Quaternary paleoclimates, chap. 2 *of* Morrison, R.B., ed., Quaternary nonglacial geology, conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. K-2, p. 35-41.

Smith, G.I., and Church, J.P., 1980, Twentieth-century crustal deformation in the Garlock fault-Slate Range area, southeastern California: Geological Society of America Bulletin, part 1, v. 91, p. 524-534.

Smith, G.I., and Haines, D.V., 1964, Character and distribution of nonclastic minerals in the Searles Lake evaporite deposit, California: U.S. Geological Survey Bulletin 1181-P, 55 p.

Smith, G.I., and Pratt, W.P., 1957, Core logs from Owens, China, Searles, and Panamint basins, California: U.S. Geological Survey Bulletin 1045-A, 62 p.

Smith, G.I., and Street-Perrot, F.A., 1983, Pluvial lakes of the western United States, chap. 10 *of* Wright, H.E., Jr., ed., Late-Quaternary environments of the United States: Minneapolis, University of Minnesota Press, p. 190-212.

Smith, G.I., Troxel, B.W., Gray, C.H., Jr., and von Huene, Roland, 1968, Geologic reconnaissance of the Slate Range, San Bernardino and Inyo Counties, California: California Division of Mines and Geology Special Report 96, 33 p.

Smith, G.I., Barczak, V.J., Moulton, G.F., and Liddicoat, J.C., 1983, Core KM-3, a surface-to-bedrock record of late Cenozoic sedimentation in Searles Valley, California: U.S. Geological Survey Professional Paper 1256, 24 p.

Smith, G.I., Friedman, Irving, and McLaughlin, R.J., 1987, Studies of Quaternary lakes—III. Mineral, chemical, and isotopic evidence of salt solution and crystallization processes in Owens Lake, California, 1969-1971: Geochimica et Cosmochimica Acta, v. 51, p. 811-827.

Smith, G.I., Bischoff, J.L., and Bradbury, J.P., 1997, Synthesis of the paleoclimatic record from Owens Lake core OL-92, *in* Smith, G.I., and Bischoff, J.L., eds., An 800,000-year paleoclimatic record from core OL-92, Owens Lake, southeast California: Geological Society of America Special Paper 317, p. 143-160.

Smith, R.S.U., 1978, Late-Pleistocene paleohydrology of pluvial Lake Panamint, California [abs.]: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 148.

Snyder, C.T., and Langbein, W.B., 1962, The Pleistocene lake in Spring Valley, Nevada, and its climatic implications: Journal of Geophysical Research, v. 67, p. 2385-2394.

Snyder, C.T., Hardman, George, and Zdenek, F.F., 1964, Pleistocene lakes in the Great Basin: U.S. Geological Survey Geologic Investigations Map I-416, 1 plate, scale 1:1,000,000.

Spencer, R.J., Baedecker, M.J., Eugster, H.P., Forester, R.M., Goldhaber, M.B., Jones, B.F., Kelts, K., Mckenzie, J., Madsen, D.B., Rettig, S.L., Rubin, M., and Bowser, C.J., 1984, Great Salt Lake, and precursors, Utah; the last 30,000 years: Contributions to Mineralogy and Petrology, v. 86, p. 321-334.

Stein, M., Wasserburg, G.J., Aharon, P., Chen, J.H., Zhu, Z.R., Bloom, A., and Chappell, J., 1993, TIMS U-series dating and stable isotopes of the last interglacial event in Papua New Guinea: Geochimica et Cosmochimica Acta, v. 57, p. 2541-2554.

Stine, Scott, 1990, Late Holocene fluctuations of Mono Lake, eastern California: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 78, p. 333-381.

Stuiver, Minze, and Smith, G.I., 1979, Radiocarbon ages of stratigraphic units, *in* Smith, G.I., Subsurface stratigraphy and geochemistry of late Quaternary evaporites, Searles Lake, California: U.S. Geological Survey Professional Paper 1043, p. 68-75.

Thompson, R.S., Toolin, L.J., Forester, R.M., and Spencer, R.J., 1990, Accelerator-mass spectrometer (AMS) radiocarbon dating of Pleistocene lake sediments in the Great Basin: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 78, p. 301-313.

Van Horn, R., 1979, Surficial geologic map of the Salt Lake City South Quadrangle: U.S. Geological Survey Miscellaneous Investigations Map I-1173, scale 1:24,000.

Varnes, D.J., and Van Horn, R., 1984, Surficial geologic map of the Oak City area, Millard County, Utah: U.S. Geological Survey Open-File Report 84-115, 3 sheets, scale 1:31,680.

Varnes, D.J., and Van Horn, R., 1991, Surficial geologic map of the Oak City area, Millard County, Utah: U.S. Geological Survey Open-File Report 91-433, 4 sheets, scale 1:31,680.

Warren, C.N., and Schneider, J.S., 1989, Nelson Lake, San Bernardino County; museum records and collections from important early sites: San Bernardino County Museum Association Quarterly, v. 36, no. 2, p. 3-50.

Wells, S.G., and Dohrenwend, J.C., 1985, Relict sheetflood bed forms on late Quaternary alluvial-fan surfaces in the southwestern United States: Geology, v. 13, p. 512-516.

Wells, S.G., Anderson, R.Y., McFadden, L.D., Brown, W.Y., Enzel, Y., and Miossec, J.L., 1989, Late Quaternary paleohydrology of the eastern Mojave River drainage, Southern California; quantitative assessment of the late Quaternary hydrologic cycle in large arid watersheds: New Mexico Water Resources Research Institute, Technical Completion Report, Project No. 14-08-0001-G1312, WRRI Report No. 242, 253 p.

Wentworth, C.K., 1922, A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, no. 5, p. 377-392.

Winograd, I.J., Szabo, B.J., Coplen, T.B., Riggs, A.C., and Kolesar, P.T., 1985, Two-million-year record of deuterium depletion in Great Basin ground waters: Science, v. 227, p. 519-522.

Winograd, I.J., Szabo, B.J., Coplen, T.B., and Riggs, A.C., 1988, A 250,000-year climatic record from Great Basin vein calcite; implications for Milankovitch theory: Science, v. 242, p. 1275-1280.

Winograd, I.J., Coplen, T.B., Landwehr, J.M., Riggs, A.C., Ludwig, K.R., Szabo, B.J., Kolesar, P.T., and Revesz, K.M., 1992, Continuous 500,000-year record from vein calcite in Devils Hole, Nevada: Science, v. 258, p. 255-260.

Appendixes 1–3

Appendix 1. Measured Sections

Stratigraphic sections were measured in various parts of Searles Valley to provide specific examples of the sediments that are present. Most measurements were made on single steep to vertical exposures, but some sections (identified as "composite") combine measurements made on exposures scattered over a small area (such as 0.5 km^2). Most sections primarily describe sediments assigned to the Searles Lake Formation. For each described interval of sediments from this formation, the unit or subunit assignment for it is listed in the left column. Where sediments belonging to the older gravel unit or the Christmas Canyon Formation were included in the measured section, they are so identified in the unit column. Where samples were collected from a bed in a section for ^{14}C dating, the uncorrected results and the material that was dated are given. Sediment terminology follows Wentworth (1922); colors modified by parenthetical expressions follow Goddard (1951); parenthetical data in the headings (for example, S125-3) are the author's field-note numbers.

The sections are arranged according to the alphanumeric order of the locality designation (explained in the section on field and laboratory methods); for example, Section G5-k is followed by G10-m, and then by H14-r. Descriptive locations and the approximate elevation at the top of the section (in feet and meters) are also given.

Most of the geographic features cited in the headings to help locate the sampled sites are shown on the base maps of plates 1-4 or in figure 1*B*. However, three informal geographic terms are also used: (1) The Pinnacles bar refers to the 2-km-long lacustrine bar that trends southeast from the east end of the Spangler Hills into The Pinnacles area (fig. 1*B*); (2) the Poison Canyon amphitheater refers to the 0.5-km-wide stream-cut area of low relief at the mouth of Poison Canyon where it enters Searles Valley from the west; and (3) State Highway 178 enters the study area from the west and runs eastward adjacent to Salt Wells Valley Wash—technically, this highway ends at the dirt road leading southeast to The Pinnacles, but in fact it continues as a paved road east and north through Trona to northern Searles Valley, then continues north and east to Panamint and Death Valleys.

Section C36-h. Sediments exposed on northwest side of unnamed canyon in Slate Range (S125-3); approximate elevation at top of section: 2,040 ft (620 m).

Unit	Thickness (m)	Description
A	1.0	Gravel, gray, pebble to cobble sizes, well rounded, equivalent to layer that veneers bench on southeast side of canyon, lacustrine.
	4.6	Sand, medium to fine, orange yellow.
	1.5	Sand and silt, yellow but more orange in upper half.
	0.3	Gravel, well rounded, gray.
	1.6	Sand, pebbly, tan.
	1.5	Sand, medium, grayish orange.
	0.3	Silt, efflorescences.
	1.5	Gravel, alluvial(?), pebbles and cobbles well rounded, sorting fair to poor, grayish orange.
	1.2	Sand, medium grading down to very fine, yellow orange, lower part distinctly lacustrine.
	0.6	Gravel, pebble size, well rounded, lacustrine.
	1.5	Silt, light tan.
	1.2	Sand, very coarse to medium, calcareous soil at top.
	3.0	Sandy gravel, pebbles well rounded, some deltaic bedding, upper third possibly alluvial.
	6.0±	Alternating pebbly sand and sandy gravel, grayish orange, poorly exposed, lacustrine(?).
Older gravel (unit og)	15±	Gravel, angular pebbles to cobbles, some boulders, grayish orange, alluvial; resting on fractured, orange-stained plutonic rock.

Total thickness: 40.8+ m (134+ ft)

Section E25. Composite description of sediments exposed along north wall of canyon in Argus Range, west of Borosolvay site (S79-1, 2, 3); approximate elevation at top of section: 2,040 ft (620 m).

Unit	Thickness (m)	Description
B	10	Pebble gravel, light gray, well rounded, numerous fragments of rounded nodose tufa, lacustrine.
Tufa (unit st)	7.5	Lithoid tufa, in form of towers and shoreline benches.
A	3.0	Silt and sand, grading up to gray gravel, subangular to subrounded, lacustrine.
	6.1	Gravel, fragments 2-30 cm (average 15 cm), angular, sandy matrix, gray to slightly orange, alluvial.
	1.2	Sand and gravel, gray, lenticular, lacustrine.
Older gravel (unit og)	10+	Gravel, fragments to 2 m, medium to dark gray, alluvial.

Total thickness: 37.8+ m (124+ ft)

Section G5-k. Description of sediments exposed along north side of Copper Queen Canyon, Slate Range (S92-1); approximate elevation at top of section: 2,160 ft (660 m).

Unit or Subunit	Thickness (m)	Description
AB	0.6	Boulder gravel, fragments to 0.6 m across, subangular, dark orange brown, alluvial.
sa3	1.5	Gravel, fragments to 10 cm, gray, uncemented, lacustrine.
	1.5	Sand, medium, tan, uncemented, lacustrine.
	0.3	Gravel, fragments to 20 cm, either alluvial or a lacustrine lag gravel.
	0.9	Gravel, pebbles to granules, well sorted, gray, well cemented, lacustrine.
	1.2	Sand, medium to coarse, soft, tan, lacustrine.
	0.3	Gravel, pebble size.
	1.0	Gravel, pebbles to granules, well sorted, gray, cemented, lacustrine
sa2	1.3	Gravel and sand, tan, poorly sorted, alluvial (or colluvial).
	0.6	Gravel, fragments 3 to 6 cm, angular, alluvial.
sa1	1.5	Sand, fine to coarse, soft, tan, lacustrine.
	1.8	Sand, medium to coarse, gray, lacustrine.
	0.3	Gravel and sand, dark brown to gray, very well cemented, locally flaggy, lacustrine.
Older gravel	1.5	Colluvial gravel, fragments mostly pebble sizes, tan.
	3.1	Sand and gravel, fragments to 30 cm in size form 3% of unit, tan, well bedded, alluvial.
(unit og)	1.5+	Sand and gravel, fragments to 60 cm form 10% of unit, upper 1 m has concentrations of calcite on boulders (soil?).

Total thickness: 18.9+ m (62+ ft)

Section G10-n. Composite description of sediments exposed on both sides of canyon leading to Standard Mine, Slate Range (S94-7); approximate elevation at top of section: 2,280 ft (695 m).

Unit	Thickness (m)	Description
Older gravel	10	Gravel, poorly sorted mixture of sand and pebble to cobble gravel, some boulders, tan to slightly orange, poorly bedded, alluvial.
(unit og)	1	Gravel, pebble to cobble, little finer matrix, gray, well rounded and sorted, lacustrine.
	3	Gravel, alluvial, like above.
	1	Gravel, lacustrine, like above.
	12	Sand and gravel, 60% to 80% of unit is sand or silt, balance is pebbles and cobbles, scattered boulders to 2 m across, gray to tan, alluvial.
	1	Gravel, mostly pebble size, gray, lacustrine but not as well rounded as gravels above.
	2+	Sand and gravel, like 12-m-thick alluvial gravel above.

Total thickness: 30+ m (98+ ft)

Section H14-r. Sediments exposed on north side of Poison Canyon amphitheater area; see fig. 7; approximate elevation at top of section: 1,850 ft (564 m).

Unit or Subunit	Thickness (m)	Description
BC	2+	Sand, medium to very coarse, fairly well sorted, moderate yellowish brown (10YR5-6/4-6), very faint bedding, pebble lag gravel on surface, pebbles 0.5 to 3 cm long, numerous fragments of pale brown (5YR5/2) nodose tufa on surface.
sb4	2.7	Silt, slightly calcareous to very calcareous, silt contains high percentage of greenish-gold mica flakes, 0.2- to 0.3-m-thick lenticular marl layers in lower third, unit is moderate yellow (5Y6/2) on weathered surfaces, light olive brown (5Y5/2) on fresh surfaces, lower half mostly massive, faint bedding in upper half; in fig. 7, this unit exposed only on north wall of wash that is concealed behind nearest low ridge.
sb3	3.1	Marl, yellowish gray (5Y8/1) on weathered surface, grayish orange (10YR7/4) on fresh surface, very faint thin bedding on weathered surface, nearly massive on fresh surface; near middle of unit and 0.5 m apart are two hard, nearly white 2-cm-thick silty limestone layers and a 1-cm-thick nodose tufa layer.
sb2	0.7	Sand, fine to very coarse, some granules, interbeds of greenish-gold-colored mica-rich silt, yellowish brown (5YR6/4), faint bedding, scattered mollusks.
	0.5	Silt, calcareous, yellowish gray (5Y7/2), lower third well bedded, upper part faintly bedded.
	1.1	Sand, like 0.7-m-thick bed above, faint bedding, dips on beds variable
sb1	3.6	Marl and silt, layer is mostly calcareous silt, yellowish gray (5Y7/2) to very pale orange (10YR8/2) on weathered surfaces, grayish orange (10YR7/2) on fresh surfaces; locally includes a hard, 0.3-m-thick, basal marl that is yellowish gray (5Y7/2) and has beds 1 to 2 mm thick; 1-cm-thick nodose tufa bed present 1 m below top of bed, basal contact sharp in most areas; in fig. 7, this unit is basal bed of nearest exposure. (Exposed on east face of small ravine)
	1.8	Pebble sand, sand is coarse to very coarse, pebbles to 3 cm long and granules make up a few percent, grayish orange (10YR7/2) on weathered surface, yellowish brown (10YR6/4) on fresh surface, locally cross bedded, indurated.
	0.2	Marl, yellowish gray (5Y7/2), high percentage of greenish-gold mica flakes.
	1.6+	Pebble sand, like 1.8-m-thick unit above.

Total thickness: 17.3+ m (57+ ft)

Section H23-a. Sediments mapped as Unit B exposed on north side of Poison Canyon amphitheater (HQI32E-59); approximate elevation at top of section: 1,840 ft (560 m).

Subunit	Thickness (m)	Description
sb6	0.6	Silt, very thinly bedded, moderately well indurated, light brownish gray (5Y6/1); contact with unit C at top of bed.
	4.9	Silt, thinly bedded, slightly indurated, light brownish gray (5Y6/1).
	4.9	Cross-bedded medium sand in lower third, flat-bedded sandy gravel in middle; flat-bedded pebble sand in coarser layers could be fluvial.
sb5	0.9	Silt, micaceous, calcareous, well sorted, greenish yellow (7Y7/6).
	4.6	Silt, faint bedding 20-50 cm thick, weathers with puffy surface, calcareous, yellowish gray (5Y6-8/1).
	0.6	Silt, micaceous, calcareous, well sorted, greenish yellow (7Y7/6).
	0.9	Marl, thinly bedded, slightly indurated, yellowish gray (5Y8/1).
sb1	1.2	Fine to pebbly sand, poorly sorted, moderate yellowish brown (10YR5/4), local concentrations of mollusks; contact with unit sab3 at base of bed.

Total thickness: 18.6 m (61 ft)

Section H23-f. Sediments exposed on west side of Poison Canyon amphitheater, north of State Highway 178 (HQ131-21); approximate elevation at top of section: 1,900 ft (580 m).

Unit or Subunit	Thickness (m)	Description
sc3	6.8	Silt to very fine sand, calcareous (calcite, aragonite) beds laminated to 2 cm, yellowish gray (5Y7/2) to pale olive (10Y6/2), weathers puffy but well cemented on fresh surfaces.
sc2	0.7	Sand, coarse to very coarse, locally well bedded.
sc1	2.3	Silt to very fine sand, calcareous (dolomite, calcite, aragonite), beds laminated, weathers yellowish gray (5Y7/2) and pale olive (10Y6/2), well cemented on fresh surface.
BC	1.5	Sand, very fine to medium, calcareous (calcite), well bedded, dark beds to 2 cm thick alternate with light beds, contorted in lower part, soft, thickness varies, more tan than underlying sand.
sb6	2.5	Sand, medium to very coarse, arkosic, poorly sorted and rounded, some pebbles to 2 cm, poor bedding, conspicuous amounts of pink feldspar, very pale.
sb5	2.5	Sand, very fine, well sorted, yellowish gray (5Y7/2) calcareous (calcite), well bedded, 0.3 m bed of orange sand 1 m up from base, a few snails and clams, lower half weathers puffy, light tan to white.
	0.7	Silt to very coarse sand, calcareous (aragonite, calcite), laminated at base, light gray (5Y7/1-2) to white, contact with underlying sand is sharp, some sand incorporated in basal 30 cm.
---------------disconformity---------------		
sab3	1.0	Sand, coarse to very coarse, a few pebbles, conspicuous amounts of pink feldspar, fragments subangular to subround; bedding distinct, 2-30 cm thick, light olive gray (5Y6/2), snails and clams in lower 0.5 m.
	2.0	Sand, fine to very fine, bedded, well sorted, micaceous, soft, calcareous (calcite), light olive gray (5Y6/2); weathers slightly puffy; snails and clams noted throughout, common in middle part.
	2.5	Sand, medium to very coarse, pebbly, massive to poorly bedded, brownish yellow (10YR6/6) to light gray (5Y7/2), fragments subangular to subrounded, poorly sorted, weathers to smooth surface; a few snails and clams in upper 0.5 m.

Section H23-f. Sediments exposed on west side of Poison Canyon amphitheater, north of State Highway 178 (HQ131-21); approximate elevation at top of section: 1,900 ft (580 m). —Continued

Unit or Subunit	Thickness (m)	Description
sab3	1.3	Sand, fine to coarse, bedded and cross-bedded, ripple marks, olive yellow (5Y6-7/2), weathers slightly puffy, some thin layers of very coarse sand.
sab2	1.8	Silt to very fine sand, a few layers of very coarse sand, thinly bedded to laminar, calcareous (calcite), weathers puffy, snails, light olive gray (5Y6-7/2).
sab1	1.0	Sand, coarse to very coarse, massive, pale yellow (5Y7/4), may be fluvial, local lag gravel at top.
	1.8	Sand, medium to very coarse, well bedded, beds 1-4 mm defined by dark or calcareous layers, very few pebbles, pale yellow (5Y7/4), snails throughout.
	0.9	Sand, very fine, beds thin to massive, calcareous (calcite), pale yellow (5Y7/2).
	0.6	Sand, medium to coarse, well rounded, calcareous pods, pale yellow (5Y7/2), snails, some pebbles, cobbles, and clay balls, some orange streaks and pods.
	1.5	Sand to silt, very fine, calcareous (calcite, dolomite), weathers puffy, locally laminated, pale yellow (5Y7/2).
	0.7	Sand, fine to very coarse, bedded, well indurated, calcareous pods in upper part; pale yellow (5Y7/4) with streaks of light yellowish brown (10YR6/4).
	0.2	Sand to silt, very fine, massive, weathers puffy, soft, pale yellow (5Y7/2).
A	2+	Silt, calcareous (calcite), greenish, massive to faint bedding, 1-mm pods of (secondary?) halite, weathers pale yellow (5Y8/3).

Total thickness: 34.3+ m (113+ ft)

Section H23-g. Sediments exposed along highway, south side, east of Poison Canyon (HQ132E-53B); approximate elevation at top of section: 1,800 ft (550 m).

Subunit	Thickness (m)	Description
sb6	1.2	Sand, medium to very coarse, pebbly, slightly orange near top, numerous small mollusk shells.
sb5	2.0	Silt to very fine sand, tan, faint thin bedding, locally laminated, uniform texture; contact with underlying unit gradational here but distinct channels exposed west of section.
	2.5	Silt to fine sand, orange-gray, mostly massive, some cross-beds.
	1.0	Marl, weakly laminated, oolitic; ^{14}C date: 18,560±10 yr (marl).
sb4	0.5	Sand, fine, well sorted, faintly bedded, dark orange, contains mollusk shells, pods of ulexite, gypsum near base; ^{14}C date: 18,600±130 yr (shells).
sb3	2.0+	Marl, bedding thin to laminar, locally contorted, thin lenses of fine sand, gypsum crystals.

Total thickness: 9.2+ m (30+ ft)

Sections H23-h and H24-e. Generalized description of sediments exposed south of State Highway 178, southwest side of Poison Canyon amphitheater (HQ 131-44); approximate elevation at top of section: 1,850 ft (565 m).

Unit or Subunit	Thickness (m)	Description
CD	2	Sand, tan to orange.
C	2	Silt, white to light green, laminated.
	1	Sand, very coarse, cross-bedded, tan to pink; ^{14}C date: 14,210±120 yr (shells).
	3	Silt, white to light green, laminated, layer of tufa near base, tuff bed 1-2 m up from base; ^{14}C date: 10,430±120 yr (tufa).
B	1	Gravel, lenticular, grades laterally and downward into medium to very fine sand, orange to greenish gray, cross-bedded, large quantities of tan tufa at or near top.
	3	Silt, greenish to white, lenticular, massive to thin bedded, some interbeds of sand.
sab7	1	Orange sand and gravel, prominent lag gravel at top.
	1	Silt, greenish, lenticular.
	1	Sand, orange, not as coarse as overlying sand bed; contact with unit below gradational in many areas.
sab6	5	Alternating fine sand and silt, greenish gray to tan, resistant sand lenses commonly less than 10 cm thick; prominent 0.5-2 m silt at base; ^{14}C date: 32,100±1,200 yr (organic matter).
sab5	1	Sand, very coarse, cross-bedded, persistent, tan to pinkish gray in some areas, orange in others; local prominent gravel layer at top which in places contains concentration of snails, clams, and ulexite.
sab4	3	Silt, white in lower part, grades to greenish in upper part, thin orange tuff(?) bed overlain by thin nodose tufa bed in many areas; ^{14}C date: 27,800±1,200 yr (organic matter), 28,800±400 yr (tufa carbonate).
sab3	1	Sand, locally very fine but generally medium to fine, well to poorly sorted, some deltaic beds, interbedded with tan to orange silt, in places has up to 1-m thick interbeds of silt; ^{14}C date: 35,000±1,600 yr (shells).
sab2	2	Silt, greenish, generally massive.
sab1	1	Sand, tan to orange, lag gravel at base, very sharp top contact.
A?	1	Silt, white to tan, very fine.

Total thickness: 29 m (95 ft)

Section H28-f. Composite description of sediments exposed north of State Highway 178, east of "The Y" (HQ131E-14, 17, & 22); approximate elevation at top of section: 2,000 ft (610 m).

Unit or Subunit	Thickness (m)	Description
sc3c	3.6	Sand, very coarse, well sorted, pebble lag on surface, light olive gray (5Y6/1) with lighter silt at base, abundant nodose tufa fragments.
sc3b	1.8	Sand, medium to very coarse, some pebbles and clay, beds 1-5 cm thick, calcareous (aragonite, calcite), grayish orange (10YR6/4), deltaic bedding dips east.
sc3a	7.0	Silt, sandy near top, calcareous (aragonite, calcite, traces of dolomite), yellowish gray (5Y7-8/1-2), mostly massive, some beds 0.3-0.5 m thick, weathers with "popcorn" surface.
sc2	2.2	Sand, medium to coarse, well sorted, 1-m-thick light colored silt layer in middle, moderate yellowish brown (10YR5/4), some mollusks.

Section H28-f. Composite description of sediments exposed north of State Highway 178, east of "The Y" (HQ131E-14, 17, & 22); approximate elevation at top of section: 2,000 ft (610 m). —Continued

Unit or Subunit	Thickness (m)	Description
sc1	5.1	Clay separated by thin beds of very fine sand, calcareous (calcite, some aragonite and dolomite), basal 1 m is well exposed, beds 3 to 10 mm thick, yellowish gray (5Y7/2), similar to underlying unit except not contorted, small patches of nodose tufa at base, upper 4 m weathers with "popcorn" surface, gypsum crystals in top 1 m, oolitic sand and fragmentary tufa 1 m up from base.
-----------------	---unconformity---	-----------------
B	1.8	Silt and clay, calcareous (calcite), contains black organic(?) fragments, light olive gray (5Y6/2), darker on fresh surface, white salt efflorescence on expose surfaces, pronounced bedding 1-10 mm thick, locally contorted, sticky and plastic when moist.
AB	0.3+	Boulder gravel, well cemented, alluvial; exposed in floor of wash.

Total thickness: 16.8+ m (55+ ft)

Section H30-g,h. Generalized description of sediments exposed in Salt Wells Valley (HQ131-58, 63); approximate elevation at top of section: 1,960 ft (595 m).

Unit	Thickness (m)	Description
Tufa (unit st)	1.0	Lithoid tufa, massive, 5 cm of pale brown (5YR5/2) nodose tufa on upper surface.
A	2.0	Silt and grayish orange (5YR6/2) tufa fragments, jumbled; basal contact flat and smooth.
	1.0	Silt or fine sand, massive, yellowish gray (5Y8/1), much of "sand" appears to be composed of indurated clay fragments.
	0.3	Clay-fragment breccia, yellowish gray (5Y8/1), grades into underlying unit.
	3.3+	Silt, light green (10Y6-7/1-2), laminae 1-3 mm thick, 5-10 mm apart; lower 3/4 of section poorly exposed.

Total thickness: 7.6+ m (25+ ft)

Section I8-l,m,n. Composite description of sediments exposed near wash on both sides of railroad tracks (S-58-7,9,10 and S-59-7); approximate elevation at top of section: 1,660 ft (505 m).

Unit or Subunit	Thickness (m)	Description
D	0.03	Gravel, thinly scattered fragments of dark rocks to 3 cm long; matrix is silt of underlying unit.
	0.1	Silt, soft, saline efflorescences, moderate brown (5YR4/4).
CD	1.5	Gravel, alluvial, poorly bedded and sorted, pebbles to 6 cm, pale yellowish brown (10YR6/2), weak soil in top 20 cm, calcareous pods 1 to 2 cm across.
	0.2	Sand, many pebbles, massive, color and sorting as above.
sc4	1.0	Clay and silt, calcareous (calcite, aragonite), massive to very faintly bedded, undeformed, grayish yellow green (5GY5-7/1-2), plastic when moist.
	0.6+	Clay and silt, like above but with contorted bedding.

Total thickness: 3.43+ m (11+ ft)

Section I18-a. Section exposed on south side of Poison Canyon Wash; approximate elevation at top of section: 1,700 ft. (520 m). Illustrated by figure 22.

Unit or Subunit	Thickness (m)	Description
CD	4 to 11	Mostly sand and pebble gravel, alluvial, some thin lacustrine-silt layers; alluvial material is tan, poorly sorted, local rippled foreset beds, subrounded to subangular fragments of rock, nodose tufa, laminated silt, and reworked mollusk shells (^{14}C date: 16,200 ± 300 yr); silts are generally massive, but locally well bedded; beds dip to 50°; partially developed lag gravel on top surface; unit rests on a deformed and subaerially eroded surface of underlying unit.
sc4	1 to 6	Sand and silt, lacustrine; sand is fine to very fine, tan to olive, well bedded to massive, well sorted; some silt layers contain much clay, which is massive, light green, calcareous, very plastic when wet, strongly contorted as a result of soft-sediment deformation; rests on subaerially eroded surface cut on underlying unit.
sc3	1 to 2	Silt and clay, lacustrine; calcareous, characterized by numerous thin white laminae.

Total thickness: about 12 m (39 ft) but variable (see fig. 22)

Sections I19-p,q,r and I30-a. Composite description of sediments exposed west of railroad, east of Spangler Hills (HQ132E-31); approximate elevation at top of section: 1,700 ft (820 m).

Unit or Subunit	Thickness (m)	Description
sc3	0.5	Silt, white, very prominently laminated.
sc2	0.2	Sand, very coarse, tan, ripple marks.
sc1	0.2	Silt, white, prominently laminated.
BC	0.2	Sand, medium to very fine, tan to gray, well bedded, weakly developed ripple marks.
sb6	0.6	Silt, greenish gray, thinly bedded but not laminated, some snails and clams.
sb5	0.3	Sand, medium to very coarse, tan, some tan-orange zones.
	0.5	Silt to very fine sand, very light greenish gray, weakly laminated in upper half, prominently laminated in lower half.
sb4	0.3	Sand, very fine to medium, tan with streaks of orange, well bedded.
	0.8	Silt, white, prominent laminae.
sb3	0.2	Sand, fine, gray-orange, ripple marks in upper part.
sb2	0.5	Silt and very fine sand, massive, greenish gray; ^{14}C date: 19,150±150 yr (marl).
sb1	0.5	Sand, medium, orange, some ulexite, snails and clams.
	0.3+	Silt, greenish, massive.

Total thickness: 5.1+ m (17+ ft)

Section I30-b,c,g. Composite section of sediments exposed east of alluvial fan on east end of Spangler Hills (5-21-89); approximate elevation at top of section: 1,720 ft (525 m).

Unit or Subunit	Thickness (m)	Description
D	0.1-1	Gravel with silt matrix, very angular (fragments possibly fractured by salt wedging) to slightly rounded fragments near toe of fan, average 10 cm in size, range from 2 to 30 cm (100 to 200 m east of fan, average 5 cm in size, range from 2 to 20 cm), fragments are grayish black (N2) to dark brown (5YR3-4/2-4); probably alluvial gravel reworked by near-shore lacustrine processes.
	1-2	Silt and sand, some granules and pebbles, grayish orange (10YR6-7/2-4), massive, saline efflorescence, weathers with puffy surface, pods of ulexite 10 to 20 cm below surface found locally (some years); deposited on uneven surface.
CD	1+	Gravel, alluvial, fragments average about 20 cm in length, range from 5 to 30 cm; fragments, which have lighter colors than those in unit D, are moderate brown (5YR3-5/4-6); poorly sorted sand matrix is grayish orange (10YR7/4), poorly bedded.
sc1	2+	Marl, laminated, on fresh surfaces, 1- to 2-mm-thick laminae are white (N9), intervening thicker layers are grayish yellow green (5GY6-7/2) to pale olive (10Y6-7/2).

Total thickness: 6+ m (20+ ft)

Section I32-j. Description of sediments exposed near north end of wash that dissects southeast end of The Pinnacles bar (HQ132-10); approximate elevation at top of section: 1,740 ft (530 m).

Unit or Subunit	Thickness (m)	Description
Tufa	0.5	Nodose tufa, dark brown.
BC	0.6	Sand, very coarse, numerous pebbles, grayish tan, cross-bedded, well cemented.
B	1.1	Silt and very fine sand, grayish tan, coarse sand layer in middle, weathers with “puffy” surface.
sa4	0.3	Sand, fine to very coarse, grayish tan, cross-bedded, well cemented lens of lithoid tufa at base.
sa3	0.8	Silt to very fine sand, scattered pebbles, greenish gray, massive, weathers puffy, lithoid tufa lens at base.
sa2	0.3	Coarse sand and pebbles, poorly sorted, subangular fragments, orange, alluvial.
sa1	0.8	Sand, medium to very fine, extensively cross-bedded; pods of lithoid tufa, defluidization structures.
	0.6	Silt and very fine sand, greenish, laminar bedding.
	1.0+	Sand, coarse to very fine, arkosic, lenses of pebble conglomerate, tan-gray, streaks of orange stain, numerous defluidization structures.

Total thickness: 6.0+ m (20+ ft)

Section I32-r. Composite description of sediments exposed along wash cutting crest of The Pinnacles bar (PTK5023B-16 and -37); approximate elevation at top of section: 1,760 ft (535 m); see figure 9.

Unit or Subunit	Thickness (m)	Description
Tufa	1.2±	Tufa, lithoid and nodose, lenticular; base of tufa ^{14}C-dated: 13,700±350 yr.
sa4	0.5	Gravel, angular to subangular cobbles; forms crest of large lacustrine bar.
sa3	1.0	Pebble to cobble sand and gravel, calcareous, poorly sorted, lacustrine; nearby marl lens, 1 m below top of bed, ^{14}C-dated: 21,910±100 yr.
	4.0	Silt, sand, and gravel, interbedded, lacustrine, poorly sorted, massive to well bedded, medium to light gray, well indurated, calcareous.
	0.3	Tufa, lithoid type, bedded, medium gray.
sa2	0.5	Gravel, alluvial, poorly sorted, small angular fragments, grayish orange, lenticular, moderate to strong calcareous soil developed locally on unit (sediments exposed only in small area on west side of wash; horizon expressed as a 30-cm-thick calcareous soil elsewhere in wash).
sa1	0.5	Sand, calcareous, indurated, gray, lacustrine.
	0.5	Silt, calcareous, white; basal contact flat, no channels exposed, lacustrine.
	0.4	Gravel and coarse sand, lacustrine, very calcareous.
Christmas Canyon Formation (ccg)	1.8+	Gravel, alluvial, very poorly sorted, volcanic-rock cobbles.and boulders to 30 cm long constitute 20-30 percent of unit, matrix is poorly sorted very coarse sand, strong calcareous soil developed in upper 1.3 m (upper 0.2 m nearly solid calcareous sand), composed of horizontal and vertical stringers of sandy calcite, 2-5 cm across, and a zone rich in pedogenic clay which is yellowish gray (5Y7/2) to light olive (5Y5/2) (olive hues, strongest in finest beds, fade out downward).

Total thickness: 10.7+ m (35+ ft)

Section K24-p,q. Composite description of sediments exposed along Teagle Wash (V175-4); approximate elevation at top of section: 1,960 ft (595 m).

Unit or Subunit	Thickness (m)	Description
B	0.1	Pebble pavement, composed of older tufa (unit ot) fragments.
AB(?)	0.6	Conglomerate, light gray fragments of older tufa, faint orange stain on top fragments.
sa3	0.3 0.3	Tufa, uncommon variety of lithoid type. Sand, tan, well bedded, calcareous, vertical defluidization structures.
sa2	1.8	Gravel, alluvial, greenish to tan, top of soil zone is orange or reddish, vertical columnar (desiccation?) structures 0.6 m long.
sa1	1.2	Tufa, lithoid, massive.
	0.3	Silt, white, very calcareous, massive to well bedded
	0.3	Sand, very coarse, calcareous, dark tan.
Christmas Canyon Formation (ccg)	3.0+	Gravel, alluvial, arkosic, tan; soil developed on equivalent surface 250 m to west.

Total thickness: 7.3+ m (24+ ft)

Section L8-k. Sediments exposed along southeast sideof Teagle Wash, 2 km southwest of The Pinnacles (PTK5023B-7, 31); approximate elevation at top of section: 1,850 ft (565 m); see figure 16.

Unit or Subunit	Thickness (m)	Description
sc3	1.2	Silt, greenish, thinly laminated.
sc2	0.3	Sand, tan, very fine to medium, ripple marks.
sc1	0.3	Silt, greenish, thinly laminated, gypsum crystals.
BC	0.4	Pebble gravel, tan to slightly orange, abundant nodose tufa fragments, well rounded.
B	1.0	Silt, some very fine sand, well bedded, not laminated like overlying subunits.
	0.4	Gravel, pebbles, some cobbles, and well-rounded nodose tufa, intermixed clay and silt; some fragments stained orange, 65 percent of cobbles from Spangler Hills, balance from south.
	0.9	Silt, some sand, well bedded not laminated, ^{14}C age in upper part: 16,970±400 yr (marl).
sab7	0.3	Gravel, pebbles and very coarse sand, pebble lag gravel at top contact, cross bedded, stained dark orange, some fragments still have vestige of desert varnish; rests with sublacustrine unconformity on underlying sediments.
sab6(?)	1.5	Silt and sand, gray, discontinuous lenses of orange to gray pebble gravel or sand, some probably alluvial, some cross-bedded lacustrine layers.
sab5(?)	0.4	Sand, medium to very coarse, grayish orange, cross-bedded, possibly alluvial in part.
sab3(?)	0.3	Sand and silt, silt is laminated, unit lenses out to south.
	0.2	Sand, some pebbles near base, orange, lens of silt at base, lower contact broadly undulating.
	1.2	Gravel, alluvial, a few rock fragments to 20 cm, rounded green-clay fragments (containing ostracodes) to 70 cm. Basal contact flat and sharp
Christmas Caynon Formation (ccg)	1.2+	Gravel, matrix is arkosic, pale red (10R5-6/2-4), rounded pebbles and cobbles composed of dacite, andesite, and vesicular basalt.

Total thickness: 9.6+ m (31+ ft)

Section M18-k. Sediments exposed on east side of Randsburg Wash (PTK4-141-4); approximate elevation at top of section: 1,860 ft (565 m).

Unit	Thickness (m)	Description
C	1.0	Gravel, fragments well rounded, to 10 cm diameter, lacustrine, possible faint soil at top.
	0.5	Sand, very coarse, some pebbles, probably lacustrine, could be alluvial.
	0.5	Silt, yellowish green, tufa at base.
	1.2	Gravel, sand with streaks of pebbles, alluvial(?), yellowish gray, slightly cross-bedded.
	1.2	Gravel, cobbles and boulders, poorly sorted, faintly bedded, light olive gray, alluvial.
	0.5	Silt, yellow green, nodose tufa at base, ^{14}C age: 12,000±400 yr (tufa).
B	3.8	Gravel, pebbles and cobbles to 15 cm across, well rounded, some layers of lacustrine sand.
	0.3	Silt and sand, greenish.
	0.5	Sand, some pebbles, tan, well bedded.
AB	2.5+	Gravel, cobbles and boulders, mostly angular, poorly sorted sand matrix, tan, moderately indurated, poorly exposed.

Total thickness: 12.0+ m (39+ ft)

Appendix 2. Sediment Studies

During the early mapping stages of this project, a study of the lacustrine and alluvial sediments exposed in Searles Valley was initiated by Robert J. McLaughlin and the author. Its goal was to establish field criteria—objective and numerical if possible—for distinguishing lacustrine and alluvial sediments. Because silt and marl beds rarely require special criteria to eliminate an alluvial origin, our studies concentrated on sand and gravel units. Most of the criteria that we developed are summarized in table 1; additional criteria were those summarized by Clifton (1973), who also conferred with us in the field.

Field criteria involving visual estimates of grain-size distributions have to be verified by laboratory measurements. For our study, we concentrated on the sediments exposed at 27 sites in Searles Valley. The field observations, measurements, and sampling were carried out by McLaughlin and the author, and all of the laboratory analyses and the ensuing plotting of data and statistical calculations were by McLaughlin. A selection representing about half of the clastic-size data that we collected are presented in tabular form in table 12.

Field measurements at each site were made as follows: We (1) selected an exposure that included a well-exposed bed or series of beds, (2) measured, marked, and photographed the most suitable 5-m-wide study area, (3) visually identified and separated one or more beds for detailed study, (4) where possible, outlined two or more rectangular clast-count zones that contained 100 or more clasts greater than 10 mm in length, and (5) designated two or more vertical zones along which we would make visual grain-size estimates and take channel samples for laboratory grain-size analysis at a later time. Several beds were sampled at many sites, but the clast-count ("field measurements") and channel-sample ("laboratory measurements") data listed for each site in table 12 represent the same beds.

Lacustrine deposits were classified as representative of one of three depositional environments commonly represented by coarse clastic deposits in Searles Valley, namely beach, deltaic, and bar. These classifications were based largely on bed morphology, inferred wave-energy requirements, bedding character, vertical position in the stratigraphic sequence, and horizontal position in the basin. Alluvial deposits were not subdivided.

Within the clast-count zones, clasts greater than 10 mm long in the longest exposed dimension were measured with a millimeter scale. Measurements continued until the lengths of about 100 clasts had been recorded. These data were then sorted to permit calculation of the percentage of clasts whose exposed sizes fall between each integer in the phi scale (ø), giving a measure of the distribution of clast populations. In the phi scale, ø = -log x (grain diameter), where the log is to base 2 and the grain diameter is in millimeters (Krumbein, 1934). Records were kept of the largest clast in the sampled bed and the largest one in the 5-m-wide outcrop of the same unit or subunit ("Maximum clast sizes" in table 12). Visual estimates were also made of the volume percentage of clasts larger than 10 mm in the bed being sampled; these estimates were made independently by two or more people, when possible, and averaged ("Clast % in bed" in table 12).

The channel-sample material was brought to the laboratory, treated with HCl to disaggregate the fragments (Searles Valley does not have large areas that contribute limestone or dolomite clasts), and sieved using a stack of 8-inch sediment-sizing screens graduated in intervals of 1 ø unit. After mechanical shaking of each sample for about 10 minutes, the fraction retained by each screen was weighed to the nearest 0.01 gram. The results of these analyses, in weight percent, are also listed in table 12.

Results of the laboratory-determined size analyses were then plotted against the ø scale on logarithmic probability graph paper (if sediment grains have a perfectly log-normal distribution, they plot as a straight line on this type of graph paper). This enables one to estimate the value of ø for any percentile of the sample. To determine the desired statistical parameters, the ø values for 1, 5, 16, 50, 84, and 95 percentiles were determined from the plots (table 13, left columns). From these values, the mean size, standard deviation, skewness, and kurtosis represented by each sample were calculated (table 13, right columns). Average values for each of the four sediment categories give some measure of the processes active during deposition in each environment.

In table 12, the coarse-clast and fine-clast statistical data each separately add to 100 percent. Plotting the coarse-clast data on the logarithmic probability graph paper generally showed a curve similar to that from the fine-clast data, but offset. Attempts to extend the laboratory-determined size-distribution curve into the coarse-clast section by combining the clast-count data and the clast-percentage estimate did not work well. Although the field estimates may contain substantial errors, most of the difficulty is attributed to the difference in the nature of the data from the field and laboratory measurements. Sieve measurements sort on the basis of the intermediate dimension of each fragment, and directly measure the weight and weight-percent of the entire population of those fragments. In contrast, our field measurements determined the longest exposed dimension of fragments, but we found no satisfactory way to estimate the probable relation between that dimension and those fragments' intermediate dimension, or to estimate the relative weight percentage of those large, usually irregularly shaped fragments.

These data (tables 12 and 13) also show how statistical measures based on size-distribution studies of sediments can be misleading when the sediment contains clasts too large to include in the laboratory sample. For example, the averaged values for the mean size and standard deviation of alluvial-fan environments (table 13) suggest that such deposits contain smaller and better sorted materials than the lacustrine-bar gravel deposits, but the pebble counts and large/largest clast data show that most alluvial materials have a notably wider total range in fragment size and are clearly less well sorted than the bar gravel deposits. Similarly, the skewness values, in which positive values indicate a predominance of fine material and negative values indicate the opposite, suggest that the bar gravels contain a higher percentage of fine material than the fan materials, whereas inclusion of the coarsest alluvial fragments in the statistical calculations would almost certainly reverse this relation. The kurtosis, which indicates the peakedness or flatness of size-distribution curves, suggests that the beach and deltaic environments produce near-normal distributions, whereas the alluvial gravels—without the very large clasts included—appear to have a better-than-normal sorting and the bar gravels a much poorer-than-normal sorting.

Table 12. Distribution of clast sizes in sediments from Searles Valley.

Size terms[1] and dimensions (mm) of fragments and screen openings; other data	Phi Scale	Lacustrine "beach" environments			Lacustrine "deltaic" environments						
		Site Number									
		1	2	3	4	5	6	7	8	9	10
I. Field measurements (population-percent of clasts in successive phi-scale categories[2])											
Maximum clast sizes[3]		29/35	-/-	-/-	-/12	40/185	-/-	-/12			
Boulders		0	0	0	0	--	0	0	0	0	0
Cobbles — 256 —	-8										
		0	0	0	0	--	0	0	0	0	0
Cobbles 128	-7										
		0	0	0	0	--	0	0	0	0	0
— 64 —	-6										
		0.9	0	0	0	--	0	0	0	0	0
Pebbles 32	-5										
		22.2	0	0	0	--	0	0	0	0	0
Pebbles 16	-4										
		76.9	0	0	0	--	0	0	0	0	0
Pebbles 8	-3										
Clast % in bed (est.)[4]		10	0	0	0	3[5]	0	0	0	0	0
II. Laboratory measurements (weight-percent of sediments caught between screens of indicated sizes)											
Pebbles — 64 —	-6										
		0	0	0	0	0	0	0	0	0	0
Pebbles 32	-5										
		0	0	0	0	0	0	0	0	0	0
Pebbles 16	-4										
		0	0.2	0	0	0	0.2	0	0	0	0
Pebbles 8	-3										
		0.8	1.4	0.4	0.7	0.1	0.1	2.1	1.2	0	1.7
— 4 —	-2										
Granules		1.8	17.9	6.2	3.4	0.8	2.6	2.8	2.2	0.7	9.9
— 2 —	-1										
Very coarse sand		7.4	41.4	37.2	7.5	4.1	4.2	5.7	5.2	1.1	19.4
— 1 —	0										
Coarse sand		57.7	36.4	53.0	14.1	9.1	8.5	15.0	13.5	5.5	21.1
— 0.5 —	1										
Medium sand		24.9	1.3	1.9	26.6	33.1	31.4	30.4	36.1	56.9	32.0
— 0.25 —	2										
Fine sand		2.2	0.5	0.6	31.2	40.7	42.5	38.2	36.7	32.2	12.5
— 0.125 —	3										
Very fine sand		0.8	0.2	0.2	10.9	7.1	6.8	4.4	3.1	1.8	1.2
— 0.0625 —	4										
Silt and clay		4.4	0.7	0.5	5.6	5.1	3.7	1.4	2.0	1.8	2.2
III. Other data											
Percent $CaCO_3$([6])		4.4	21.6	23.3	22.3	13.2	3.8	17.8	15.3	8.6	9.7
Map unit or Subunit[7]		Ts	sab6	sab6	sa	sab5	sb	sbc	sbc	sbc	sbc
Plate no.		*2B*	*2A*	*2A*	*3A*	*3A*	*3A*	*3A*	*3A*	*3A*	*3A*
Location[8]		M19-1	C3-r	C3-r	H13-c	H24-f	I7-g	I19-f	I19-f	I17-m	I17-m

[1] Follows usage of Wentworth (1922).

[2] Clasts greater than 10 mm long; 100 or more fragments in most counts.

[3] Maximum dimension of pebbles greater than 10 mm in count area/maximum in exposed bed; in millimeters.

[4] Clasts greater than 10 mm in size; average of two- or three-person estimate.

[5] "Pebbles" and "cobbles" are carbonate-rimmed mud balls.

[6] Determined by comparing sample weight before and after treatment with cold, dilute HCL.

[7] Map unit or subunit label used on plate specified.

[8] See text and plate 1 for explanation of location system.

[9] Lacustrine layer interbedded in older gravel unit.

Table 12. Distribution of clast sizes in sediments from Searles Valley. —Continued

Size terms[1] and dimensions (mm) of fragments and screen openings; other data	Phi Scale	Lacustrine "bar" gravel environments — Site Number 11	12	13	14	15	16	17	18
I. Field measurements (population-percent of clasts in successive phi-scale categories[2])									
Maximum clast sizes[3]		81/152	53/60	100/190	50/125	100/100	95/200	70/150	35/80
Boulders		0	0	0	0	0	0	0	0
— 256 —	-8								
Cobbles		0	0	0	0	0	0	0	0
128	-7								
Cobbles		2.0	0	1.0	0	4.6	5.0	0.7	0
— 64 —	-6								
Pebbles		15.0	4.0	16.0	6.4	5.4	19.0	14.5	1.0
32	-5								
Pebbles		24.0	34.0	46.0	41.6	44.5	37.0	35.5	27.6
16	-4								
Pebbles		59.0	62.0	37.0	52.0	45.5	39.0	43.9	71.4
8	-3								
Clast % in bed (est.)[4]		50	14	35	58	62	40	75	4
II. Laboratory measurements (weight-percent of sediments caught between screens of indicated sizes)									
— 64 —	-6								
Pebbles		0	0	16.1	0	17.3	51.4	22.8	0
32	-5								
Pebbles		0	0	27.5	26.6	28.8	18.4	19.3	0
16	-4								
Pebbles		3.0	8.8	19.5	31.1	21.8	10.4	24.7	0.7
8	-3								
Pebbles		12.8	9.5	7.0	15.5	10.8	2.9	16.2	20.6
— 4 —	-2								
Granules		50.3	19.9	4.4	5.0	2.6	1.2	5.3	45.8
— 2 —	-1								
Very coarse sand		16.6	25.7	5.5	3.5	0.9	1.1	2.0	21.4
— 1 —	0								
Coarse sand		2.2	21.3	3.8	1.4	1.8	1.3	1.2	4.6
— 0.5 —	1								
Medium sand		1.2	5.0	1.7	0.8	9.3	2.3	2.3	1.1
0.25	2								
Fine sand		3.6	1.4	0.7	2.4	6.0	3.1	4.4	3.6
— 0.125 —	3								
Very fine sand		3.8	1.0	0.6	3.4	0.5	1.5	1.3	1.5
— 0.0625 —	4								
Silt and clay		6.5	7.4	13.2	10.3	0.2	6.4	0.5	0.7
III. Other data									
Percent $CaCO_3$(6)		17.9	7.3	1.4	4.2	1.8	n.d.	5.2	n.d.
Map unit or Subunit[7]		og[9]	sal	sal	sal	sab6	sb	sc	sclc
Plate no.		1	*3A*	4	4	*2A*	1	1	*2A*
Location[8]		G15-m	I23-r	I32-r	I32-m	C15-k	I7-a	C14-1	C34-a

Table 12. Distribution of clast sizes in sediments from Searles Valley.—Continued

Size terms[1] and dimensions (mm) of fragments and screen openings; other data	**Phi Scale**	**Alluvial "fan" environments**								
		Site Number								
		19	20	21	22	23	24	25	26	27
I. Field measurements (population-percent of clasts in successive phi-scale categories[2])										
Maximum clast sizes[3]		370/455	50/50	80/410	165/165	90/190	52/400	60/400	50/130	115/265
Boulders		1.0	0	0	0	0	0	0	0	0
— 256 —	-8									
Cobbles		4.1	0	0	0	0	0	0	0	0
128	-7									
		15.3	0	1.4	1.1	3.3	0	0	0	1.8
— 64 —	-6									
Pebbles		24.5	1.2	18.2	3.4	14.0	4.0	17.0	2.0	7.3
32	-5									
		46.9	23.4	41.9	26.1	34.7	3.0	47.0	26.0	22.9
16	-4									
		8.2	75.4	38.5	69.4	48.0	65.0	36.0	72.0	68.0
8	-3									
Clast % in bed (est.)[4]		70	29	60	6	32	58	62	8	25
II. Laboratory measurements (weight-percent of sediments caught between screens of indicated sizes)										
— 64 —	-6									
Pebbles		7.4	0	6.5	0	0	0	0	0	0
32	-5									
		29.6	0	19.8	0	0	1.3	0	1.1	0
16	-4									
		15.4	6.2	17.9	3.9	8.9	6.9	3.7	2.2	3.6
8	-3									
		15.2	11.4	12.9	19.2	8.5	7.0	7.3	3.1	9.5
— 4 —	-2									
Granules		10.4	21.4	11.6	19.9	14.5	11.9	17.5	9.3	23.2
— 2 —	-1									
Very coarse sand		7.7	22.7	13.0	14.1	20.1	17.9	22.7	24.2	23.3
— 1 —	0									
Coarse sand		5.3	15.3	8.7	10.5	20.1	16.8	20.0	27.2	17.0
— 0.5 —	1									
Medium sand		3.5	9.2	3.8	8.7	14.9	18.3	12.7	18.1	10.4
— 0.25 —	2									
Fine sand		3.0	5.9	2.0	8.6	8.8	13.4	9.2	7.7	6.2
— 0.125 —	3									
Very fine sand		1.9	2.5	1.1	5.9	2.6	5.8	3.6	1.6	2.5
— 0.0625 —	4									
Silt and clay		0.6	5.4	2.7	9.2	1.6	0.7	3.1	5.5	4.3
III. Other data										
Percent $CaCO_3$(6)		n.d.	n.d.	n.d.	n.d.	n.d.	4.3	4.3	5.2	n.d.
Map unit or subunit[7]		og	ccg	saa	sab	sab5	sab5	sab5	scd5	al
Plate no.		1	4	1	1	*2A*	*2A*	*2A*	*3A*	1
Location[8]		G15-m	L8-k	B25-h	C8-m	C3-h	C15-k	C15-k	I8-f	F31-m

Table 13. Statistical parameters for 27 sediment samples, based on sieve analyses listed in table 12.

[Values in phi units; formulas and references below. $\bar{x}$ = mean of values for given group of sites. For locations of sample sites, see table 12.]

Sample site	Phi values at successive percentiles						Mean size (phi)	Standard deviation (phi)	Skewness	Kurtosis
	Phi 1	Phi 5	Phi 16	Phi 50	Phi 84	Phi 95				
Lacustrine "beach" environments										
1	-1.8	-0.5	+0.2	+0.8	+1.6	+3.0	+0.87	0.88	+0.200	1.50
2	-2.3	-1.6	-1.1	-0.2	+0.4	+0.8	-0.30	0.74	-0.185	0.60
3	-1.7	-1.1	-0.6	-0.1	+0.6	+0.9	+0.03	0.60	-0.283	0.66
$\bar{x}$ (1-3)	-1.9	-1.1	-0.5	+0.2	+0.9	+1.6	-0.20	0.74	-0.089	0.92
Lacustrine "deltaic" environments										
4	-1.8	-0.8	+0.4	+1.9	+3.1	+4.1	+1.80	1.42	-0.107	0.81
5	-1.0	0.0	+1.1	+2.1	+2.9	+4.0	+2.03	1.06	-0.081	1.22
6	-1.5	-0.4	+1.0	+2.1	+2.8	+3.8	+1.97	1.09	-0.206	1.33
7	-2.7	-1.0	+0.4	+1.8	+2.7	+3.3	+1.63	1.23	-0.260	0.87
8	-2.0	-0.6	+0.6	+1.8	+2.6	+3.1	+1.67	1.06	-0.249	0.85
9	-0.7	+0.7	+1.3	+1.8	+2.4	+2.9	+1.88	0.61	+0.045	1.00
10	-2.2	-1.5	-0.7	+1.0	+2.0	+2.7	+0.77	1.32	-0.225	0.55
$\bar{x}$ (4-10)	-1.7	-0.5	+0.6	+1.8	+2.6	+3.4	+1.67	1.11	-0.155	0.95
Lacustrine "bar" gravel environments										
11	-6.6	-2.7	-2.0	-1.3	+0.6	+4.5	-0.90	1.74	+0.537	1.77
12	-3.9	-3.6	-2.2	-0.5	+0.9	+6.5	-0.60	2.31	+0.144	2.26
13	-5.5	-5.8	-5.0	-3.7	+1.0	+10.0	-2.57	2.14	+1.567	1.63
14	-5.7	-5.2	-4.3	-3.3	+2.0	+6.2	-1.87	3.31	+0.674	0.81
15	-4.4	-5.2	-4.7	-3.8	+1.0	+2.2	-2.50	2.55	+0.653	0.30
16	-6.3	-6.7	-5.9	-4.6	-1.0	+4.5	-3.83	2.99	+0.554	1.37
17	-2.9	-5.5	- 4.9	-3.7	-1.9	+2.2	-3.50	1.92	+0.366	1.57
18	-3.5	-2.5	-2.1	-1.4	-0.3	+2.2	-1.27	1.16	+0.377	1.61
$\bar{x}$ (11-18)	-4.8	-4.6	-3.9	-2.8	+0.3	+4.8	-2.13	2.26	+0.609	1.42
Alluvial "fan" environments										
19	-5.8	-5.2	-4.6	-3.2	-0.3	+2.1	-2.70	2.19	+0.400	0.70
20	-4.3	-3.2	-2.1	-0.5	+1.7	+4.1	-0.30	2.06	+0.209	0.92
21	-5.1	-4.7	-4.2	-2.5	+0.3	+2.4	-2.13	2.20	+0.312	0.58
22	-3.6	-2.9	-2.2	-0.5	+2.9	+5.0	-0.07	2.48	+0.363	0.54
23	-5.0	-3.5	-2.1	-0.1	+1.8	+2.9	-0.13	1.95	-0.044	0.64
24	-4.2	-3.3	-1.9	+0.3	+2.2	+3.2	+0.20	1.01	-0.017	0.58
25	-3.9	-2.7	-1.6	-0.1	+2.0	+3.3	+0.10	1.81	+0.150	0.67
26	-4.1	-2.4	-1.0	+0.4	+2.0	+4.2	+0.47	1.75	+0.109	1.20
27	-3.8	-2.8	-1.8	-0.7	+1.7	+3.8	-0.27	1.88	+0.368	0.89
$\bar{x}$ (19-27)	-4.4	-3.4	-2.4	-0.8	+1.6	+3.4	-0.54	1.93	+0.206	0.75

Formulas and sources for parameters:

$$\text{Mean size} = \frac{(\text{phi } 16)+(\text{phi } 50)+(\text{phi } 84)}{3} \quad \text{(Folk and Ward, 1957)}$$

$$\text{Standard deviation} = \frac{(\text{phi } 84)-(\text{phi } 16)}{4} + \frac{(\text{phi } 95)+(\text{phi } 5)}{6.6} \quad \text{(Folk and Ward, 1957)}$$

$$\text{Skewness} = \frac{(\text{phi } 84)+(\text{phi } 16)-2(\text{phi } 50)}{2[(\text{phi } 84)-(\text{phi } 16)]} + \frac{(\text{phi } 95)+(\text{phi } 5)-2(\text{phi } 50)}{2[(\text{phi } 95)-(\text{phi } 5)]} \quad \text{(Mason and Folk, 1958)}$$

$$\text{Kurtosis} = \frac{[(\text{phi } 95)-(\text{phi } 5)]-[(\text{phi } 84)-(\text{phi } 16)]}{[(\text{phi } 84)-(\text{phi } 16)]} \quad \text{(Inman, 1952)}$$

Appendix 3. Evidence and Reasons Used for Determining Slopes, Elevation Ranges, and Ages of Segments of Lake-History Diagrams (Figures 39*C* and 40*C*)

[Unless otherwise noted, required data are plotted in figures 39*A*, 39*B*, 40*A*, and 40*B*. "Section" refers to measured sections in appendix 1.]

Age ranges of segments (ka)	Evidence and rationale
170–150	Mud layers interbedded with thin monomineralic saline layers characterize upper part of Mixed Layer (Smith and others, 1983, p. 12-13, fig. 5., pl. 1); plotted lake fluctuations are diagrammatic; depths near 110 ft. (34 m) deposited saline layers, depths near 170 ft. (52 m) deposited mud.
150–149	Lack of subunit sa1 exposures below 1,720 ft suggests rapid rise of lake.
149–145	Deposition of lithoid tufa, as both tabular and pinnacle-shaped masses, present at base of subunit sa1 between 1,720 and 1,960 ft near and southwest of The Pinnacles (section I32-r); process required shallow water and significant time.
145–140	Overflow into Panamint Valley had to start early enough for Panamint Lake to fill well before Searles Lake began to recede at 120 ka; insoluble components show most rapid decrease during early part of this interval.
140–118	Overflow period; end of overflow based on compilation by Jannik (1989) of chloride budget and periods of its loss caused by overflow from Searles Lake.
118–117	Diagenetic mineral zone, commencing at about 117 ka, indicates increasing salinity of lake water caused by shrinking lake.
117–111	Deposition of lithoid tufa on top of subunit sa1, at and below 1,960 ft (sections H30-g and K24-p), required shallow water near this level for an appreciable time.
111–102	Presence of monomineralic salt beds, increasing percentages of acid-insoluble minerals, diagenetic minerals abundant; considered equivalent to subunit sa2.
102–86	Deposition of tabular (and pinnacle-shaped ?) lithoid tufa masses at base of subunit sa3, between 1,740 and 1,960 ft (section I32-j), near and southwest of The Pinnacles, required significant interval; diagenetic analcime deposition ended at 91 ka; increased CaO content of core KM-3 centered at 86 ka, inferred to be correlative with highest level of this lake rise, which is plotted approximately proportional to CaO content.
86–81	Increase in acid-insoluble percentage, period precedes salt deposition.
81–77	Monomineralic salt beds present in subsurface deposits.
77–71	Perennial lake beds found in cores; moderate decrease in acid-insoluble content implies lake expansion; overlying salt layers require this expansion to be followed by contraction.
71–69	Monomineralic salt bed present in subsurface deposits.
69–58	Increasing(?) CaO content, little change in acid-insoluble content, authigenic mineral zone ends at 58 ka.
58–50	CaO content increases to highest level in core at 50 ka, rapid decrease in acid-soluble content; age of maximum lake-level elevation based on position of highest CaO value; possible overflow into Panamint Valley.
50–46	Overlying monomineralic salt bed requires shrinking of lake.
46–45	Presence of monomineralic salt bed, very low CaO content.
45–41	Return to high levels of CaO and continued intermediate-level acid-insoluble content.
41–39	Decrease in lake level required to allow deposition of bar gravels of subunit sa4 near The Pinnacles (section I32-r).
39–36	Deposition of subunit sa4.
36–35	Thin salt bed found in about a quarter of the GS-series of cores about 3 ft below top of Bottom Mud (Haines, 1959; Smith, 1979, p. 16).
35–32	Perennial-lake deposits constitute upper 3 ft of Bottom Mud.

32–24	High stands based on table 9, low stands based on mineralogy of salt beds in Lower Salt (Smith, 1979, p. 88-89); stillstand prior to 24 ka reflects time needed to develop desert varnish and AB soil now found on subunit sab7 and alluvial deposits of this unit (see text).
24–22.5	Perennial-lake deposits, unlaminated and coarsely laminated, separate salt bed in Parting Mud (fig. 36) from Lower Salt.
22.5–15.5	High stands proportional to CaO content of GS-16 core, lowstands from table 9; high stands plotted as still-stands at estimated level because marl layers are thicker than sand layers in subunits sb1 to sb6 in area east of Spangler Hills (pls. 3*A*, 4).
15.5–15.0	Lake-level decrease required prior to following lowstand.
15.0–13.5	Lowstand elevation from table 9, duration of lowstand from CaO and acid-insoluble data and from distribution of coarsely laminated bedding in core GS-16 (fig. 36); substantial duration of lowstand also indicated by soil developed on surface of unit BC alluvial beds.
13.5–12.5	Lake rise and stillstand based on prominent bars deposited at base of unit C, north and south ends of basin, 1,900 to 1,940 ft elevation.
12.5–10.5	Highstands and lowstands from table 9.
10.5–9.5	Estimated duration of Upper Salt deposition, which appears to have been uninterrupted (Smith, 1979, p. 112).
9.5–6.0	Period of minimal deposition on exposed surface of Upper Salt.
6.0–2.0	General age control based on one ^{14}C age (3.5 ka) from wood in Overburden Mud (Stuiver and Smith, 1979, p. 73); lake level from table 9; duration of lake stand is only an estimate (see text).
2.0–0	Lack of evidence of younger lakes suggests period of minimal deposition on surface of Overburden Mud.

This page left blank intentionally.

Produced in the Western Region, Menlo Park, California
Manuscript approved for publication, June 22, 2006
Text edited by Peter Stauffer and Julia Thomas
Plates edited by Jan Zigler and Carolyn Donlin
Layout and design by Judy Weathers

USGS
science for a changing world

Smith—**Late Cenozoic Geology and Lacustrine History of Searles Valley, Inyo and San Bernardino Counties, California—Professional Paper 1727**